Hierarchical goal effects on center of mass velocity and eye fixations during gait

Mohammad R. Saeedpour-Parizi1 · Shirin E. Hassan2 · Tayebeh Baniasadi1 · Kelly J. Baute3 · John B. Shea1

Received: 19 May 2020 / Accepted: 1 August 2020 / Published online: 9 August 2020
© Springer-Verlag GmbH Germany, part of Springer Nature 2020

Abstract
The purpose of this study was to determine the effect of hierarchical goal structure of a yet-to-be performed task on gait and eye fixation behavior while walking to the location of where the task was to be performed. Subjects performed different goal-directed tasks representing three hierarchical levels of planning. The first level of planning consisted of having the subject walk to a bookcase on which an object (a cup) was located in the middle of a shelf. The second level of planning consisted of walking to the bookcase and picking up the cup which was in the middle, on the right side, or on the left side of the bookcase shelf. The third level of planning consisted of walking to the bookcase, picking up the cup which was located in the middle of the bookcase shelf, and moving it to a higher shelf. Findings showed that hierarchical goals do affect center of mass velocity and eye fixation behavior. Center of mass velocity to the bookcase increased with an increase in the number of goals. Subjects decreased gait velocity as they approached the bookcase and adjusted their last steps to accommodate picking up the cup. The findings also demonstrated the important role of vision in controlling gait velocity in goal-directed tasks. Eye fixation duration was more important than the number of eye fixations in controlling gait velocity. Thus, the amount of information gained through object fixation duration is of greater importance than the number of fixations on the object for effective goal achievement.

Keywords Goal hierarchy · Center of mass velocity · Eye fixation · Inter-limb coordination

Introduction
Goal-directed gait is a frequent activity of daily living (Bienkiewicz et al. 2014; Mlinac and Feng 2016). Despite this, a few studies have investigated how gait is affected by to be performed goals. Rosenbaum et al. (2012) demonstrated that the goals of the performer can be inferred by the way which they interact with an object for task performance, and this will allow an examination of the influence of goals on task performance. For example, it has been found that subjects tend to grasp a horizontally placed bar differently depending on which end will be placed in the downward position when the rod is moved vertically (Rosenbaum et al. 1990). According to Rosenbaum, complex planning is a hierarchy in which each subsequent plan interacts with the previous plan in the hierarchy. Researchers (Kaller et al. 2004; McKinlay et al. 2008; Ward and Allport 1997; Potts et al. 2018; van der Wel and Rosenbaum 2007) have identified goal hierarchy as a characteristic that can affect a problem’s difficulty.

Before initiating goal-directed gait, the central nervous system forms a motor plan (Winter and Eng 1995; Bucklin et al. 2019; Glover 2004) along with a set of motor commands which are predicted to accomplish task-specific goals. Kaller et al. (2004) found that correct trials correlated with longer preplanning times and shorter movement execution times. An inverse relationship between preplanning and execution of the task indicates that thoroughly planned tasks are performed faster. In addition, online planning has been demonstrated to be important for goal-directed gait (Ariani and Diedrichsen 2019; Sun et al. 2017). Online planning during goal-directed gait may be achieved using visual as
well as other sources of information such as working memory (Nadkarni et al. 2010; Rosenbaum 2009) to inform the motor system of adjustments necessary for the achievement of the desired goal. Previous studies on visually guided gait demonstrated that subjects change their gait and eye fixation behavior during the performance of either time (Cinelli et al. 2009) or path constrained tasks (Cutting et al. 1995; Fajen and Warren 2004; Higuchi 2013; Marigold and Patla 2007; Matthias et al. 2018; Panchuk and Vickers 2011). Tracking eye fixations during goal-directed gait not only gives insight into where the individual looks as they approach a target, but also indicates where they are overtly attending at any given point in time. Eye fixations also allow one to calculate the location of environmental cues used in the regulation of gait (Fowler and Sherk 2003). While earlier studies demonstrated the synchrony of eye fixations and gait in different environmental contexts, they were not designed to systematically study the influence of a hierarchical goal structure on gait. The empirical literature, therefore, assessing how the hierarchical goal structure of a task influences gait is scarce. The purpose of this study was to determine the effect of hierarchical goal structure (Rosenbaum et al. 2012) of a yet-to-be performed task on gait (Center of Mass Velocity, COM; Step Length; Step Time) and eye fixation (Fixation Duration; Number of Fixations) behavior while walking in an unconstrained manner to the location of where the task was to be performed.

To address the effect of goal complexity on gait and eye fixation behavior, subjects in the present study performed five different goal-directed tasks representing three levels of task goal complexity. The structure of tasks used was influenced by the hierarchical framework for goals described by Rosenbaum (2012). Accordingly, the first-order planning consisted of having the subject walk to a bookcase on which an object (a cup) was located in the middle of a shelf. Second-order planning consisted of having the subject walk to the bookcase and pick up the cup. Three tasks were performed for this level of planning. After walking to the bookcase, subjects picked up the cup which was in the middle of the shelf, on the left side of the shelf, or on the right side of the shelf. Third-order planning was to walk to the bookcase, pick up the cup located in the middle of the shelf, on the left side of the shelf, or on the right side of the shelf. The participant may have integrated the three plans to perform the tasks (Land et al. 2013; Lashley 1951; Rosenbaum et al. 2011). In this case, we would expect to find a difference in gait and eye fixation behavior during the walk to the bookcase across the first-, second-, and third-order planning conditions. This is because the overall difficulty of the first plan would be increased by the additive effects of the second and third plans. The change in gait associated with this strategy may be the result of increasing demand for attentional resources (Nadkarni et al. 2010). In this case, an increase in task difficulty would result in an increase in time to perform the task. Alternatively, there is evidence that effort to perform a task increases with task difficulty, resulting in a decrease in time to perform a task, and this relationship has become known as the “goal difficulty-performance relation” (Locke and Latham 2002). Croxson et al. (2009) found that activity in the striatum, including the putamen, correlated with the anticipated effort for an action. Furthermore, the putamen was identified by Kurniawan et al. (2010) as being responsible for the evaluation of effort cost. That is, whether or not a goal is worth the effort to attain it.

Methods

Subjects

Eight normally sighted college students (mean age ± standard deviation: 21.4 ± 1.4 years, six female) participated in the study. All subjects completed the Edinburgh Handedness Inventory (Oldfield 1971), and were right-hand (score 86.1 ± 13.2) and right-foot dominant. None of the subjects had a history of neurological, musculoskeletal disorders, or other disorders that would limit mobility at the time of participation, according to self-report. The Institutional Review Board of Indiana University Bloomington approved the study. All subjects gave informed consent before participation in the study.

Equipment

This experiment used two Microsoft Kinect cameras. Several studies have evaluated the Kinect sensors against a gold standard motion capture system concerning the accuracy of tracked landmark movements (Clark et al. 2012; Dutta 2012; Galna et al. 2014) and found a good-to-excellent agreement between the two motion-registration systems for spatiotemporal gait parameters and time. A customized visual studio C++ application based on the Kinect SDK 2.0 was developed and used to detect, track, and record human pose and motion for post-analysis. The application tracked and recorded the 3D locations, i.e., the x, y, and z coordinates (X = Mediolateral, Y = Vertical, Z = Anteroposterior), of 25
body parts and joints based on an RGB-D sensor at 30 Hz. The operating field of view for the Kinect V2 had a range of 0.5–4.5 m and a 70° horizontal and 60° vertical view angle (Microsoft, Inc.). Because our goal-directed gait task was 7.5 m in length (see “Procedures”, Fig. 1), a Multiple-Kinect system was used to cover a longer distance. To convert a subject’s two skeletons into one, which arose from using multiple cameras, a geometric transformation was used (Horn 1987) with customized MATLAB code (MathWorks, Inc. Natick, MA). For calibration, subjects were asked to stand stationary in three points (10 s for each), and the body parts were recorded by the multi-Kinect system.

Subjects’ gaze was tracked using a Pupil Labs head-mounted eye tracker. The eye tracker has a gaze accuracy of 0.6° and the field of view of the scene camera was 100° diagonal. The eye tracker included three miniature video cameras: two “eye” cameras (one for each eye) which captured the image of the subject’s eye at 200 Hz, and one “scene” camera which captured the image scene that the subject was viewing at 120 Hz. For this study, the eye-tracking software developed by Pupil Labs (Kassner et al. 2014) was used. After subjects put on the eye tracker, a nine-point calibration was performed whereby an experimenter held a printed calibration marker 2 m in front of the subject. Subjects were required to follow the marker with their eyes while holding their head still. A nine-point calibration was used, because this calibration method covered the entire field of view of the subject’s scene camera. After calibration, subjects were instructed to look at certain areas of the room, and if there were differences between the subject’s gaze (in the software) and the area points in the room, the calibration procedure was repeated.

Procedures

Figure 1 shows the experimental set-up. Subjects stood barefoot with both feet at the start position. The start position was 7.50 m from and directly opposite the 1.84 m (height) × 0.90 m (width) × 0.22 m (depth) bookcase with two shelves. The lower shelf was 0.88 m and the upper shelf was 1.23 m above the ground. An empty 16 oz cup (the “target”) measuring 15.87 cm in height and 8.30 cm in diameter and weighing 275.23 g was located in the middle of the lower shelf. Subjects received an auditory “ready” signal followed by an auditory “go” signal. Upon receiving the go signal, subjects walked to the bookcase at a self-selected pace. They performed one of the five tasks when they arrived at the bookcase.

Subjects performed each task three times in a blocked order. Subjects were informed which of the five tasks they were to perform before each of the 15 trials. The five tasks performed by subjects were:

1. walk to the bookcase (WTB);
2. walk to the bookcase and pick up the cup which was in the middle of the lower shelf of the bookcase (PC-M);
3. walk to the bookcase and pick up the cup which was on the left side of the lower shelf of the bookcase (PC-L);
4. walk to the bookcase and pick up the cup which was on the right side of the lower shelf of the bookcase (PC-R);
5. walk to the bookcase and pick up the cup and move the cup to the upper shelf from the middle of the lower shelf of the bookcase (MCU);

The above tasks are consistent with three hierarchically ordered plans. The first task (WTB) represented one level of planning by which the subject walked to the bookcase and stopped in front of the cup. The second, third, and fourth tasks (PC-M, PC-L, and PC-R) represented two plans. In addition to the first plan, the second plan consisted of reaching and picking up the cup. The second plan had three levels represented by the cup being located in the middle of the shelf (PC-M), on the right side of the shelf (PC-R), or on the left side of the shelf (PC-L). The fifth task (MCU) represented three levels of planning where in addition to plans one and two, moving the cup to the upper shelf was the third plan.

Fig. 1 Experimental Setup. Subjects walked 7.5 m to a bookcase that had an empty 16 oz cup (the “target”) sitting in the middle of its lower shelf (0.88 m from the floor)

https://pupil-labs.com/pupil/.
Data pre-processing

Travel time

The travel time for each trial was calculated between the start time and end time. The start time was defined as the foot center local velocity minimum immediately preceding the foot center velocity first exceeding a threshold of +0.1 m/s in the anterior–posterior plane (Clark et al. 2013). The end time was defined as the time at which the subject completed their walk to the bookcase, and stood still in front of the bookcase with both feet on the ground. Each trial was normalized as a percentage of its total duration and divided into five equal segments (see Fig. 2).

Kinematics

The center of mass (COM) of a human in a uniform gravitational field is the point where all the masses of the human body are centralized. Translation of the COM from one place to another is a fundamental objective of walking. The position of each subject’s COM was found by calculating the weighted average of the position of each body segment based on anthropometric data reported by Drillis et al. (1964) and Winter (2009). An automated algorithm with a customized Matlab code was employed to extract various spatiotemporal features of the COM. The $X_{COM}$ defines the position of the subject relative to the stand position ($X = 0$). The Velocity of COM ($COM_V$) was calculated as $COM_V = \dot{X}_{COM}$ where the dot notation indicates the rate of change (i.e., $\dot{u} = \frac{du}{dt}$). The kinematic data at 6 Hz were low-pass filtered.

The rate of change of the optic field of view was also calculated using the method of Yilmaz and Warren (1995). Step length and step time were also calculated for each subject on each trial for each of the five tasks. Specifically, as described by Dolatabadi et al. (2016), step time was computed as the number of seconds that elapsed between the double support phase of one foot and a single support phase of the same foot. Step length was computed as the displacement, in millimeters, of the ankle of one foot along the z-axis during stance phase to the ankle of the opposite foot on the previous stance phase.

Eye fixations

In the current study, a fixation was defined as the subjects’ eye angle remaining within 1.6° for a minimum of 100 ms. Our rationale for a 100 ms minimum fixation duration was to ensure that there was enough time for subjects to make an action-related decision (Salthouse and Ellis 1980). Fixations were categorized as falling onto one of three possible fixation locations (environmental objects): (a) target (cup), (b) bookcase, and (c) other. An analysis of fixation duration and the number of fixations in each of the five travel time segments for all subjects, trials, and tasks showed what environmental information subjects used to walk toward the bookcase and to pick up the cup.

Statistical analysis

A 5 (task) × 5 (travel time segment) repeated-measures ANOVA was conducted on $COM_V$ to assess how movement behavior changed as a result of the performance of all five tasks (WTB, PC-M, PC-L, PC-R, and MCU). Bonferroni corrected post hoc comparisons were used to further investigate the effect of tasks on $COM_V$.

Univariate linear regressions were performed on gait step length and step time parameters to determine the relationship of these parameters with $COM_V$.

A Chi-square test was used to determine differences in the use of ipsilateral or contralateral inter-limb coordination when reaching for the cup for the four tasks in which subjects picked up the cup (PC-M, PC-L, PC-R, and MCU). Bonferroni corrected post hoc comparisons were used to further investigate the effect of the goal-directed tasks on fixation behavior.

Univariate linear regression analyses were performed to find the relation between the $COM_V$ and eye fixations on both the target and bookcase across all travel time segments as well as during each of the travel time segments and tasks.
For each measure, the three trials within each task for each subject were averaged. All analyses were performed with a customized Matlab code, and Greenhouse–Geisser epsilon was used to control violations of sphericity. An alpha level of .05 was used for all tests.

## Results

### COM velocity

Figure 3 shows COMv across travel time segments for different tasks. The velocity profiles obtained for all five tasks conform to those of many action-gaps (e.g., when reaching); the movement starts at rest, accelerates to peak velocity, and then immediately decelerates to the end of the movement. It can be seen in Fig. 3 that the effect of the goals on gait was noticeable early in the first travel time segment. This effect was an incremental increase in the COMv as the number of goals increased. In addition, at about three steps before reaching the bookcase (as shown with the dashed line in Fig. 3), subjects started to decelerate and adjust their last steps to reach the bookcase. We found that subjects began their deceleration when the rate of change in the optic field of view approximated −0.5, and that subjects kept this variable constant to have smooth braking.

The analysis of variance performed on the COMv measures confirmed the above observations. Specifically, there were significant main effects for tasks, $F(4, 28) = 6.13, p < .01$, and for travel time segment, $F(4, 28) = 76.55, p < .01$. However, the Task×Travel Time Segment interaction, $F(16, 112) = 0.702, p = .78$, was not significant. Post hoc comparisons showed that during the first and second travel time segments, COMv for the MCU, PC-M, and PC-R and PC-L tasks were significantly faster than the COMv from the WTB task ($p < .05$). During travel time segment three, the COMv from the MCU task was significantly faster than the COMv for WTB, PC-M, PC-R, and PC-L tasks ($p < .05$). During travel time segment four, the COMv was significantly faster for the MCU task than the WTB, and PC-M tasks ($p < .05$). Also, the COMv from the PC-R task was significantly faster than the COMv from the WTB task ($p < .05$).

### Relation between COMv and step length and step time

Table 1 lists the Pearson Correlation Coefficients ($r$ values) obtained from the separate univariate linear regression analyses performed for step length and step time on COMv for all tasks. The obtained $r$ values for step time were smaller than for step length for all tasks. Thus, subjects changed step length to a greater extent than step time to adjust their COMv.

### Reaching phase

The Chi-square analysis showed a significant difference in inter-limb coordination (ipsilateral or contralateral) during the reaching phase to pick up the cup ($\chi^2 = 16.19, p = .001$). As shown in Table 2, subjects showed no preference for ipsilateral or contralateral coordination in the tasks for which the cup was in the middle of the bookcase shelf (PC-M and MCU). However, subjects showed a preference for either ipsilateral (for the PC-R task) or contralateral (for the PC-L
task) inter-limb coordination when the cup was not in the middle of the bookcase shelf.

Eye fixation analysis

Figure 4 shows the mean fixation duration and number of fixations on the target and bookcase for the five goal tasks across the five travel time segments. It can be seen that fixation duration (Panel A) and number of fixations (Panel C) on the target increased to a peak at Travel Time Segment three and then decreased for Travel Time Segments four and five. The exception to this was with the MCU task for which the fixation duration and number of fixations remained high for Travel Time Segments four and five. There was a decrease in fixation duration (Panel B) and number of fixations (Panel D) on the bookcase across all travel time segments for all tasks with the exception of the MCU task for which fixation duration and number of fixations increased for Travel Time Segment five.

These observations accounted for the findings of the ANOVAs conducted on fixation duration and number of fixation measures. The ANOVA performed on fixation duration showed there were significant main effects for fixation location, $F(2, 14) = 168.12, p < .01$, and travel time segment, $F(4, 28) = 76.9, p < .01$. In addition, the Task × Fixation Location, $F(8, 56) = 2.56, p = .03$, Task × Travel Time Segment, $F(16, 112) = 2.47, p = .02$, Fixation Location × Travel Time Segment, $F(8, 56) = 32.36, p < .01$, and Fixation Location × Travel Time Segment × Task, $F(32, 224) = 3.51, p < .01$, interactions were significant.

Table 3 lists the Pearson Correlation Coefficients (r values) for eye fixations on the target obtained for the separate univariate linear regression analysis of fixation duration and number of fixations on COMV for all tasks. The correlations between number of fixations and COMV were smaller than the correlations between fixation duration and COMV for all tasks. The correlations between fixation duration on the bookcase and COMV were not significant for all tasks ($p > .05$). The exception to this was a significant correlation between fixation duration on the bookcase and COMV for the MCU task ($r = 0.38$,
No significant correlations were found between the number of fixations on the bookcase and COMv for all tasks ($p > .05$).

### Relation between eye fixation and gait characteristics

As shown in Fig. 5, a significant correlation was found between overall step length and fixation duration on the target. Significant correlations were also found between fixation duration on the target and step length for the PC-M, PC-L, PC-R, and MCU tasks ($p < .05$). The correlations between fixation duration on the target and step time were not significant for all tasks ($p > .05$). In addition, the correlations between the number of fixations on the target and step length and step time were not significant for all tasks ($p > .05$).
subjects began to decelerate and this indicates that subjects were also engaged in online planning. This finding is consistent with the subject using information from the optic flow field to evaluate their speed and their distance from the bookcase, from which they began to decelerate and adjust their last steps accordingly (Yilmaz and Warren 1995). Thus, subjects made online velocity adjustments using optic flow information from self-motion (Stanard et al. 1996). This finding is consistent with research done by Lee et al. (1982) who showed that the long-jump run-up requires a similar timing skill. Lee et al.’s (1982) results showed that athletes visually regulated the last two or three steps to the take-off board by adjusting the duration of the steps and their velocity to the board. It is interesting that subjects in our study also began to decelerate about three steps before reaching the bookcase.

Neurophysiology studies in humans have clearly pointed to a role for the posterior parietal cortex in the online updating of movements (Buneo and Andersen 2006; Desmurget et al. 1999; Pisella et al. 2000). The result of the study done by Lisi and Morimoto (2015) confirmed that the activity observed in the posterior parietal cortex is associated with the online adaptation of gait. In addition, the consistently higher correlation coefficients found between COM and step length rather than with step time in the present study (Table 1) suggests that step length played a greater role in the regulation of COM than step time. These findings are consistent with the recent research done by Wu et al. (2019) who showed that in slow walking, the relationship between gait speed and step length was 26% higher than with step time.

It can be seen in Table 2 that subjects preferred using ipsilateral lower limb support when the cup was on the right side of the bookcase shelf, a finding that is consistent with research performed by Rinaldi and Moraes (2015). However, when the target was on the left side of the shelf, subjects preferred using contralateral lower limb support. Furthermore, there was no preference for lower limb support when the cup was in the middle of the shelf. Our results describing the support limb for the different tasks, therefore, show that normal contralateral gait patterns (swinging lower limbs and upper limbs in opposition) are sometimes violated to accommodate the reach toward an object and that the central nervous system is able to break the upper-lower limb coupling at the appropriate time to exploit the upper limb forward momentum. Recent research (Nakagawa et al. 2016; Debaere et al. 2001) showed that brain activity differs in relation to the performance of ipsilateral and contralateral hand–foot combinations. Debaere et al. (2001) showed that inter-limb coordination affected activity in the supplementary motor area, and that supplementary motor area activity in ipsilateral inter-limb coordination was higher than for contralateral inter-limb coordination.

The current study also determined how vision contributed to the observed movement behaviors. Since our tasks were unconstrained, the pathway chosen by subjects was straight, and given that the cup position for the PC-L and PC-R tasks differed only by about 0.5 m from the PC-M and MCU tasks, it is surprising that the effect of task interacted with eye fixation location and travel time segment for both fixation duration and number of fixations. We found that the number of fixations on the target was high (Fig. 4c), but fixation duration was low (Fig. 4a) for the WTB task in comparison to the other tasks at Travel Time Segment three. After Travel Time Segment three, there was a reduction in the number of fixations and fixation duration on the target for the WTB task. This is evidence that in the absence of a goal hierarchy, subjects performing the WTB task paid less attention to the cup later in the task. This relationship was reversed for the other tasks (PC-M, PC-L, PC-R, and MCU) which had second- and third-level goals. For these tasks, fixation duration on the target was higher and the number of fixations was lower than for the WTB task in Travel Time Segment three. After Travel Time Segment three, fixation duration on the target for the other tasks (PC-M, PC-L, PC-R, and MCU) continued to be significantly higher compared to the WTB task, but the number of fixations was not significantly different from the number of fixations for the WTB task. Thus, subjects paid more attention to the target in these other tasks than in the WTB task. Our finding of different eye fixation behaviors across the different travel time segments between the WTB task and those tasks comprising of more goals demonstrates that subjects planned ahead and that goal hierarchy directly influences how a person surveys their environment and accordingly how they direct their attention.

The noticeable increase in fixation duration and the number of fixations on the bookcase for the MCU task at Travel Time Segment five can be attributed to the third-level goal which required subjects to lift the cup to the second shelf. The other tasks did not have this third-level goal and, therefore, their tasks were completed in Travel Time Segment five. This suggests that subjects in the MCU task were attending to the location of the second shelf, since this was where they would place the cup. Subjects adjusted their eye fixations to finish the task, and this, together with the COM deceleration findings between Travel Time Segments three and four, indicates that subjects were engaged in online planning. Ballard et al. (1995) referred to this attention as “just in time”, because individuals receive information just in time to execute an appropriate movement.

Collectively, our findings highlight that the role of vision is to “inform” the motor system about the environmental context (i.e., the relationship of the target’s location to the individual’s location and the rate of change in this relationship). The number of eye fixations has been associated with visual search (Kit et al. 2014), and the
duration of eye fixations has been associated with visual processing (He and McCarley 2010). As shown in Fig. 5, there was a significant correlation between fixation duration and step length. This finding shows the importance of eye fixations in controlling gait to the target, such as controlling step length. Furthermore, unlike previous studies which did not include fixation duration in their analyses (Hsiao and Cottrell 2007; Jacob and Hochstein 2010; Tong et al. 2017), the present study showed that fixation duration played a more important role in controlling a person’s gait than the number of fixations. As shown in Table 3, fixation duration explained approximately 32% of the variance in COMV compared to just 12% by the number of fixations. Thus, the information obtained during a fixation informs the motor system, so it can adjust gait to optimize COMV for the individual’s approach to the target. Such an adjustment would entail a modification of the step length (and to a lesser degree step time, as suggested by the results reported in Table 1), as well as the selection of the approaching foot and reaching hand coordination when approaching the target.

The implication of the relationship between the gait and vision findings found in this study is that a person must appropriately attend to environmental objects to achieve efficient and safe gait rather than just quickly look at the objects. Thus, the amount of information obtained through the fixation is more important than the fixation itself. Our experiment used a simple and unchanging environment, and so, the performance of our subjects was based on their relative distance to the bookcase and location of the target. Therefore, fixation duration was of more importance than the number of fixations since subjects would not need to visually re-explore a familiar and simple environment as much as their need to visually process pertinent information obtained through their fixations. This relationship might be opposite in studies with a changing environment for which subjects may need more visual searching (greater number of eye fixations) than information processing (longer fixation durations). Several brain regions implicated in the control of eye movements are sensitive to reward probability (Hikosaka et al. 2006). For example, the discharge activity of neurons within the monkey lateral intraparietal area varies according to the expected reward (juice) associated with an eye movement to a visual target. However, fixating a location does not usually elicit a reward in goal-directed gait. Rather, fixation shifts assist the brain to gather relevant details necessary for making a motor decision. Thus, reward alone cannot explain fixation allocation during ongoing, naturalistic behaviors. Foley et al. (2017) showed that certain lateral intraparietal area neurons change firing rates depending on the expected gain in information needed to perform the higher order planning in a two-step decision task, rather than for the expected reward associated with that subsequent action. This highlights the importance of immediate information gain in shaping action decisions.

**Conclusion**

Our results show hierarchal goals do affect both gait (COMV, step length, and step time) and eye fixations (fixation duration and number of fixations). Specifically, we showed that gait velocity increased as the number of goals in the task increased. We also found that the location of the cup on the bookcase shelf (left side, right side, or middle) rather than the normal contralateral upper–lower limb gait pattern determined whether contralateral or ipsilateral lower limb support was used to pick up the cup. Subjects also not only planned ahead for the next goal during the attainment of a current goal (demonstrated in the present study as the early adoption of increased gait velocity for tasks comprising of more goals), but also utilized online planning. We found that subjects consistently made online velocity adjustments using optic flow information from self-motion as they approached the bookcase.

Our findings also demonstrated the important role that vision plays in controlling gait velocity in goal-directed tasks. We found that fixation behavior changed as a function of goal hierarchy, and that eye fixation duration was more important than the number of eye fixations in controlling gait velocity. Thus, for effective goal achievement, the amount of information gained through object fixation is of greater importance than the number of fixations on the object. Finally, previous studies in this area were not designed to investigate the effect of hierarchical goals on performance, and therefore, their findings may have confounded the effects of variables of interest with the existing task goal structures.

**Acknowledgements** This project was partially funded by the Indiana University Vice Provost for Research through the Research Equipment Fund.

**Compliance with ethical standards**

**Conflict of interest** The authors declare that they have no conflict of interest.

**Informed consent** Informed consent was obtained from all individual subjects included in the study.

**References**

Ariani G, Diedrichsen J (2019) Sequence learning is driven by improvements in motor planning. J Neurophysiol 121:2088–2100. https://doi.org/10.1152/jn.00041.2019
Bienkiewicz MMN, Brandi ML, Goldenberg G, Hughes CML, Hermsdörfer J (2014) The tool in the brain: apraxia in ADL. Behavioral and neurological correlates of apraxia in daily living. Front Psychol 5:353. https://doi.org/10.3389/fpsyg.2014.00353

Bucklin MA, Wu M, Brown G, Gordon KE (2019) American society of biomechanics journal of biomechanics award 2018: adaptive motor planning of center-of-mass trajectory during goal-directed walking in novel environments. J Biomech 94:5–12. https://doi.org/10.1016/j.jbiomech.2019.07.030

Buneo CA, Andersen RA (2006) The posterior parietal cortex: sensorimotor interface for the planning and online control of visually guided movements. Neuropsychologia 44:2594–2606. https://doi.org/10.1016/j.neuropsychologia.2005.10.011

Cutting JE, Vishton PM, Braren PA (1995) How we avoid collisions with stationary and moving objects. Psychol Rev 102:627. https://doi.org/10.1037/0033-295X.102.4.627

Desmurget M, Epstein CM, Turner RS, Prablanc C, Alexander GE, Debaere F, Swinnen SP, Béatse E, Sunaert S, Van Hecke P, Duysens J (2001) Brain areas involved in interlimb coordination: a distributed network. Neuroimage 14:947–958. https://doi.org/10.1006/nimg.0892

Drillis R, Contini BM (1964) Body segment parameters; a survey of measurement techniques. Artif Limbs 8:44–66

Dutta T (2012) Evaluation of the Kinect sensor for 3-D kinematic measurement in the workplace. Appl Ergon 43:645–649. https://doi.org/10.1016/j.apergo.2011.09.011

Fajen BR, Warren WH (2004) Visual guidance of intercepting a moving target on foot. Perception 33:689–715. https://doi.org/10.1068/p5236

Foley NC, Kelly SP, Mhatre H, Lopes M, Gottlieb J (2017) Parietal neurons encode expected gains in instrumental information. P Natl Acad Sci USA 114:E3315–E3323. https://doi.org/10.1073/pnas.1613844114

Fowler GA, Sherk H (2003) Gaze during visually-guided locomotion in cats. Behav Brain Res 139:83–96. https://doi.org/10.1016/s0166-4328(02)00096-7

Fujiwara K, Maekawa M, Kiyota N, Yaguchi C (2012) Adaptation changes in dynamic postural control and contingent negative variation during backward disturbance by transient floor translation in the elderly. J Physiol Anthropol 31:12. https://doi.org/10.1186/1880-6805-31-12

Galna B, Barry G, Jackson D, Mhiripiri D, Olivier P, Rochester L (2014) Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson’s disease. Gait Posture 39:1062–1068. https://doi.org/10.1016/j.gaitpost.2014.01.008

Glover S (2004) Separate visual representations in the planning and control of action. Behav Brain Sci 27:3–24. https://doi.org/10.1017/S0140525X04000020

He J, McCarley JS (2010) Executive working memory load does not compromise perceptual processing during visual search: evidence from additive factors analysis. Atten Percept Psychomotor 72:308–316. https://doi.org/10.3758/APP.72.2.308

Higuchi T (2013) Visuomotor control of human adaptive locomotion: understanding the anticipatory nature. Front Psychol 4:277. https://doi.org/10.3389/fpsyg.2013.00277

Hikosaka O, Nakamura K, Nakahara H (2006) Basal ganglia orient eyes to reward. J Neurophysiol 95:567–584. https://doi.org/10.1152/jn.00458.2005

Horn BK (1987) Closed-form solution of absolute orientation using unit quaternions. J Opt Soc Am 4:629–642. https://doi.org/10.1364/JOSAA.4.000629

Hisao J, Cottrell G (2007) The influence of number of eye fixations on face recognition. J Vision 7:494. https://doi.org/10.1167/7.7.494

Jacob M, Hochstein S (2010) Graded recognition as a function of the number of target fixations. Vision Res 50:107–117. https://doi.org/10.1016/j.visres.2009.10.019

Jacobs JV, Henry SM, Nagle KJ (2010) Low back pain associates with altered activitiy of the cerebral cortex prior to arm movements that require postural adjustment. Clin Neurophysiol 121:431–440. https://doi.org/10.1016/j.clinph.2009.11.076

Keller CP, Unterrainer JM, Rahm B, Halsband U (2004) The impact of problem structure on planning: Insights from the Tower of London task. Cog Brain Res 20:462–472. https://doi.org/10.1016/j.cogbrainres.2004.04.002

Kassner M, Patera W, Bulling A (2014) Pupil: an open source platform for pervasive eye tracking and mobile gaze-based interaction. Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication (UbiComp ’14 Adjunct). Association for Computing Machinery, New York, NY, USA, pp 1151–1160. https://doi.org/10.1145/2638728.2641695

Khanmohammadi R, Talebian S, Hadian MR, Olayei G, Bagheri H (2015) Preparatory postural adjustments during gait initiation in healthy younger and older adults: neurophysiological and biomechanical aspects. Brain Res 1629:240–249. https://doi.org/10.1016/j.brainsci.2015.09.039

Kit D, Katz L, Sullivan B, Snyder K, Ballard D, Hayhoe MM (2014) Eye movements, visual search and scene memory, in an immersive virtual environment. PLoS ONE 9:e94362. https://doi.org/10.1371/journal.pone.0094362

Kurniawan IT, Seymour B, Talmi D, Yoshida W, Chater N, Dolan PJ (2014) Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson’s disease. Gait Posture 39:1062–1068. https://doi.org/10.1016/j.gaitpost.2014.01.008

Lee DN, Lishman JR, Thomson JA (1982) Regulation of gait in long jumping. J Exp Psychol Human 8:448. https://doi.org/10.1037/0096-1523.8.3.448

Lisi G, Morimoto J (2015) EEG single-trial detection of gait speed changes during treadmill walk. PLoS ONE 10:e0125479. https://doi.org/10.1371/journal.pone.0125479
Locke EA, Latham GP (2002) Building a practically useful theory of goal setting and task motivation: a 35-year odyssey. Am Psychol 57:705–717. https://doi.org/10.1037/0003-066x.57.9.705

Marigold DS, Patla AE (2007) Gaze fixation patterns for negotiating complex ground terrain. Neuroscience 144:302–313. https://doi.org/10.1016/j.neuroscience.2006.09.006

Matthis JS, Yates JL, Hayhoe MM (2018) Gaze and the control of foot placement when walking in natural terrain. Curr Biol 28:1224–1233.e5. https://doi.org/10.1016/j.cub.2018.03.008

McKinlay A, Keller CP, Grace RC, Dalrymple-Alford JC, Anderson TJ, Fink J, Roger D (2008) Planning in Parkinson’s disease: a matter of problem structure? Neuropsychologia 46:384–389. https://doi.org/10.1016/j.neuropsychologia.2007.08.018

Mlinac ME, Feng MC (2016) Assessment of activities of daily living, self-care, and independence. Arch Clin Neuropsych 31:506–516. https://doi.org/10.1093/arclin/acw049

Muhammed K, Dalmajer E, Manohar S, Husain M (2018) Voluntary modulation of saccadic peak velocity associated with individual differences in motivation. Cortex 122:198–212. https://doi.org/10.1016/j.cortex.2018.12.001

Nadkarni NK, Zabjek K, Lee B, McIlroy WE, Black SE (2010) Effect of working memory and spatial attention tasks on gait in healthy young and older adults. Mot Control 14:195–210. https://doi.org/10.1123/mcj.14.2.195

Nakagawa K, Kawashima S, Mizuguchi N, Kanosue K (2016) Difference in activity in the supplementary motor area depending on limb combination of hand-foot coordinated movements. Front Hum Neurosci 10:499. https://doi.org/10.3389/fnhum.2016.00499

Oldfield RC (1971) The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9:97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Panchuk D, Vickers JN (2011) Effect of narrowing the base of support on the gait, gaze and quiet eye of elite ballet dancers and controls. Cogn Process 12:267–276. https://doi.org/10.1007/s10339-011-0395-y

Pisella L, Grea H, Tilikete C, Vighetto A, Desmurget M, Rode G, Rossetti Y (2000) An ‘automatic pilot’ for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. Nat Neurosci 3:729–736. https://doi.org/10.1038/76694

Potts CA, Callahan-Flintoft C, Rosenbaum DA (2018) How do reaching and walking costs affect movement path selection? Exp Brain Res 236:2727–2737. https://doi.org/10.1007/s00221-018-5327-y

Rinaldi NM, Moraes R (2015) Gait and reach-to-grasp movements are mutually modified when performed simultaneously. Hum Movement Sci 40:38–58. https://doi.org/10.1016/j.humov.2014.12.001

Rosenbaum DA (2009) Walking down memory lane: where walkers look as they descend stairs provides hints about how they control their walking behavior. Am J Psychol 122:425–430

Rosenbaum DA, Marchak F, Barnes HJ, Vaughan J, Slotta J, Jorgensen M (1990) Constraints for action selection: overhand versus underhand grips. In: Jeannerod M (ed) Attention and performance XIII: motor representation and control. Lawrence Erlbaum Associates, Hillsdale, pp 321–342

Rosenbaum DA, Brach M, Semenov A (2011) Behavioral ecology meets motor behavior: choosing between walking and reaching paths. J Motor Behav 43:131–136. https://doi.org/10.1080/0022895.2010.548423

Rosenbaum DA, Chapman KM, Weigelt M, Weiss DJ, van der Wel R (2012) Cognition, action, and object manipulation. Psychol Bull 138:924–946. https://doi.org/10.1037/a0027839

Saltthouse TA, Ellis CL (1980) Determinants of eye-fixation duration. Am J Psychol 93(2):207–234. https://doi.org/10.2307/1422228

Stanard T, Flach JM, Smith M, Warren R (1996) Visual information use in collision avoidance tasks: The importance of understanding the dynamics of action. Proceedings third annual symposium on human interaction with complex systems. HICS’96, Dayton, OH, USA, pp 62–67. https://doi.org/10.1109/HUICS.1996.549493

Sun R, Cui C, Shea JB (2017) Aging effect on step adjustments and stability control in visually perturbed gait initiation. Gait Posture 58:268–273. https://doi.org/10.1016/j.gaitpost.2017.08.013

Tong MH, Zohar O, Hayhoe MM (2017) Control of gaze while walking: task structure, reward, and uncertainty. J Vision 17:28. https://doi.org/10.1167/17.1.28

van der Wel RP, Rosenbaum DA (2007) Coordination of locomotion and prehension. Exp Brain Res 176:281. https://doi.org/10.1007/s00221-006-0618-0

Ward G, Allport A (1997) Planning and problem-solving using the five-disc Tower of London Task. Q J Exp Psychol 50:49–78. https://doi.org/10.1080/713755681

Wetter OE, Wegge J, Jonas K, Schmidt KH (2012) Dual goals for speed and accuracy on the same performance task. J Pers Psychol 9:118–126. https://doi.org/10.1027/1866-5888/a000063

Winter DA (2009) Biomechanics and motor control of human movement. John Wiley & Sons, Hoboken

Winter DA, Eng P (1995) Kinetics: our window into the goals and strategies of the central nervous system. Behav Brain Res 67:111–120. https://doi.org/10.1016/0166-4328(94)00154-8

Wu AR, Simpson CS, van Asseldonk EHF, van der Kooij H, Ijspeert AJ (2019) Mechanics of very slow human walking. Sci Rep 9:1–10. https://doi.org/10.1038/s41598-019-54271-2

Yilmaz EH, Warren WH (1995) Visual control of braking: a test of the tau hypothesis. J Exp Psychol Human 21:996–1014

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.