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Energetic costs of incidental visual coupling during treadmill running

Running title: Energetic costs of incidental visual coupling

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Abstract

Purpose: We examined the role of visual-spatial information during whole body coordination. Methods: Physiological, biomechanical, and psychological indices of coordination stability were recorded while participants were visually coupled with a whole body image of themselves during treadmill locomotion. Ten participants ran on a treadmill under three visual conditions: two dynamic images (symmetrical, mirror image; asymmetrical, reversed mirror image) and one static. Performance was examined at two speeds. Results: Participants ran more economically (ml·kg⁻¹·min⁻¹) when participants were visually coupled with a symmetrical rather than an asymmetrical or static image. An asymmetrical coupling resulted in increased variability in footfall position at the faster speed, in comparison to the symmetrical and static conditions. However, at slower speeds, footfall variability and frequency were higher under both dynamic visual conditions in comparison to the static control. Conclusion: It appears that changes in physiology were only partially mediated by movement kinematics. Visual information influences treadmill locomotion and associated measures of stability even when there is no intention to coordinate.

Key words: bimanual coordination, motor control, locomotion, perception.
Energetic costs of incidental visual coupling during treadmill running

Introduction

1. Many everyday movements involve coordination between the limbs. When two limbs are moving simultaneously, there is a tendency to synchronize the movements of each in both time and space (14). In recent years, researchers examining bimanual coordination have raised questions about the principles underlying the production of these movement patterns. It appears that perceptual-spatial constraints play a dominant role in the emergence of coordinated movements both between limbs (see 15) and people (e.g., 19). In this experiment we examined whether visual information serves to encourage coordination stability in a whole-body task, where participants are visually coupled with a dynamic or static image of themselves when running on a treadmill. Of interest was the potential for various ‘effort’ related variables (i.e., physiological, biomechanical, and psychological) to provide insight into the processes that underlie coordination.

2. Researchers examining dual, upper-limb movements have shown that certain spatial-temporal patterns of movement are generated more readily than others during concurrent arm or finger movements in the horizontal plane (for reviews, see 10 and 23). These movements have been termed in-phase and anti-phase. Typically, they reflect bimanual limb motion performed in symmetry (i.e., 0° relative phase) or in asymmetry (180° relative phase) respectively. The relative stability of in-phase and anti-phase movements has been well documented since Haken, Kelso, and Bunz (9) formulated a mathematical model to describe (and predict) certain empirical phenomenon associated with these two movement patterns. Anti-phase becomes increasingly destabilized at higher frequencies, resulting in a phase transition to the more stable in-phase mode. The reasons for this behaviour have been debated, with
interpretations placing varying degrees of emphasis on neural, muscular and perceptual contributions (see 3). In-phase and anti-phase movements could be described in terms of homologous and non-homologous muscles respectively. Consequently, a motoric or neuro-muscular view of coordination dominated explanations for the relative stability of these movement patterns. Neural crosstalk, or neural leakage at higher movement frequencies was one explanation for the transition from anti-phase to in-phase (see 23). However, perceptual-spatial interpretations of this phenomenon have also been considered, with recent work leading to the suggestion that visual information plays a dominant role in determining coordination stability.

3. Original evidence supporting a dominant role for visual perception in bringing about certain coordination preferences came from research into interpersonal rather than intrapersonal coordination (18, 19, 20, 24). Rhythmic oscillations of the legs and arms of two people seated and facing each other appeared to be coordinated according to the same dynamic patterns and principles as those previously observed in single person coordination (19). This effect was even observed during unintentional, between-person coordination (18). Schmidt et al. (19) suggested that both the ‘formation’ and ‘tuning’ (see 8) of coordinated states is an inherently perceptual process. However, there is evidence that the strength of the coupling in the in-phase mode is generally greater during intrapersonal than interpersonal coordination, which would necessitate consideration of neuro-muscular factors (24).

4. A dominant role for visual-spatial information in the strength of the coupling between two effectors has also been proposed by Mechsner and colleagues (13, 14, 15). In their initial studies, Mechsner et al. (15) used three experimental paradigms: a finger oscillation task, a bimanual finger tapping task, and a bimanual
circle drawing task, where the goal of each task was visually defined. The results from these experiments showed that performance was the most stable when movements were visually in-phase (i.e., spatially symmetrical movements), regardless of the effectors and resulting neuro-muscular contributions. They concluded that the external properties of the task dominated inter-limb stability, arguing for the dominance of perceptual over motoric constraints. Although this quite extreme view has come under criticism (e.g., 17, 26, 27), the role of visual-perceptual information in influencing both the type and strength of various coordination modes is largely unquestioned. The present study was designed to explore how visual information affects measures of stability during a locomotor task when the individual is incidentally coupled with dynamic images akin to in-phase and anti-phase.

5. Researchers have typically inferred stability in coordination from movement kinematics; both the relative displacements of the effectors and the variability in between joint coordination. However, there is evidence that attentional and metabolic measures of performance are sensitive to coordination preferences, providing insights into the processes underlying different behaviours. For example, measures of RT in a dual task paradigm provide a reliable index of the resources or cognitive demands required to maintain or improve coordination (25, 29). Increases in RT or attentional load are closely linked to reductions in movement stability, as defined by kinematic variables. These findings have been replicated in both between-person and within-person bimanual coordination tasks (e.g., 24). This indicates that pattern stability during intentional bimanual coordination must be mediated by visual information.

However, an issue less understood is the degree to which unintentional or incidental visual coupling serves to encourage movement stability. Moreover, the potential for
other ‘effort’ related variables, beyond kinematics and RT, to provide an insight into the energetic costs that are associated with unintentional coupling is also equivocal.

6. There is increasing evidence that metabolic energy expenditure is a prime candidate for optimization in the establishment of movement patterns (see 1, 21, 22). In an exploratory study requiring participants to use two independent limb bicycle ergometers, Lay et al. (11) found strong inter-correlations between kinematic, metabolic, and attentional variables across lower limb relative phase patterns. However, the most economic patterns were not always the most stable; leading the authors to conclude that modes lower in metabolic energy may compete with, rather than predict dynamically stable modes. The anti-phase coordination pattern was the most efficient in terms of heart rate and oxygen consumption, whereas in-phase was the most stable pattern in terms of variability in relative phase (i.e., kinematics).

7. In summary, there are converging lines of evidence to suggest that influences external to the motor system play an important role in the stabilization and destabilization of preferred coordination modes. Moreover, these influences are observed at many levels of the motor system. According to Swinnen and Wenderoth (23), the more constraints acting in coalition with each other the more stable and accurate the coordination pattern will be. However, attentional and metabolic effects have largely been observed during intentional within-person coordination. In the following study we explore how these variables are mediated by perceptual constraints, as afforded during incidental visual coupling with phased limb movement.

8. We predicted that visual coupling with symmetrical limb movements (i.e., a dynamic mirror image) during treadmill locomotion would afford a greater level of movement stability than an asymmetrical and/or static image. Furthermore, increased levels of stability afforded under symmetrical couplings should be indexed through
increased metabolic economy and reductions in attentional load, footfall frequency, and footfall variability. An increment in treadmill speed during the experimental runs was expected to heighten the energetic demands on the motor system and accentuate any effects of the vision conditions.

**Methods**

**Participants**

9. Participants were male volunteers (N = 10) whose mean age was 21.9 yr (SD = 4.02, range = 16-28 yr). Ethical approval was obtained for the study from Liverpool John Moores University in accordance with this institution’s ethical guidelines. Participants then provided (parental where appropriate) written informed consent prior to testing. Participants were recreational runners, regularly undertaking a minimum of one and a maximum of three 20 - 30 min runs per week.

**Apparatus**

10. The treadmill used was a Woodway ELG55 running machine (Weil am Rhein, Germany). Expired air was collected using standard Douglas bag protocol. This protocol consisted of a mouthpiece connected to a circuit of Douglas bags via tubing. The mouthpiece was connected to a unidirectional valve to ensure that inspired air was acquired directly from atmospheric sources and that expired air was breathed directly into the Douglas bags. A nose clip was fitted to prevent any nasal expiration. Analysis of the expired air was carried out to obtain measures of Oxygen ($\dot{V}O_2$) and Carbon dioxide ($\dot{V}CO_2$) concentration using a Servomex 1440 gas analysis system (East Sussex, England). The Servomex 1440 was re-calibrated after every trial with gases of known concentration. Measurement of expired air volume was then performed using a Harvard dry gas meter (Kent, England). Heart rate was recorded...
using a chest and wrist mounted Polar Sports Tester telemetric heart rate monitor (Kempele, Finland).

11. A Panasonic NV-MS5 SVHS movie camera (Northampton, England) was used to film participants face-on as they ran. Concurrent visual feedback of their movements was then projected using a Sharp XG-NV2E LCD projector (Wrexham, Wales) as either a normal, reversed or static image onto a projection screen situated 2.5 m in front of the treadmill. The projection screen measured 2.5 m (h) x 2 m (w) and was sufficient for displaying life size images. A custom-built reaction timer was connected to a handgrip-style switch and to four individual red LED bulbs. The LEDs were positioned behind the projection screen so that they shone brightly through the material and were moveable so that they could be aligned with the lower arms and legs of each participant’s image on screen. The LEDs were activated by the experimenter in a pre-determined randomized sequence that was constant across participants and experimental conditions. The frequency of LED activation was constrained to no less than 20 s and no more than 90 s apart. If no reaction was initiated within 10 s of stimulus presentation, runners were reminded to maintain their focus on the screen.

12. All kinematic data were gathered using three infrared motion analysis cameras (Pro-Reflex; Qualisys, Gothenburg, Sweden) sampling at 240 Hz. The cameras were positioned at the side of the treadmill, on each participant’s right side. A reflective marker was fixed to the right lateral malleolus (ankle), the distal head of their right 5th metatarsal (toe), and the distal head of their left 1st metatarsal (toe).

Task
13. Before running under experimental conditions, each participant’s height and body mass was recorded, as was room temperature and barometric pressure. Maximal
oxygen uptake ($\dot{V}O_{2\text{max}}$) was then assessed using a graded exercise test to volitional exhaustion, as stipulated by Bird and Davison (2). All participants reached volitional exhaustion within 12 min. A series of regression analyses were performed on the $\dot{V}O_{2\text{max}}$ data so that treadmill speed (km/hr) could be standardized as a percentage of $\dot{V}O_2$ relative to each participant’s $\dot{V}O_{2\text{max}}$ score. Experimental data collection took place a minimum of three days after the $\dot{V}O_{2\text{max}}$ test and the sessions were scheduled so that there was one rest day between each run. This design was used to maintain consistency in the physiological recovery periods between runs. Sessions were also performed at approximately the same time of day (SD = 62 min).

14. During each session participants were required to run at two different speeds. The first 15 min of each run were performed at a treadmill speed equivalent to 60 % of each participant’s $\dot{V}O_{2\text{max}}$ (Slow), after which speed was increased to 80 % $\dot{V}O_{2\text{max}}$ (Fast) for the remaining 5 min. Exercise at 60 % $\dot{V}O_{2\text{max}}$ is widely recognized as a comfortable intensity at which to run in terms of the physiological effects of fatigue (12). Exercise performed at 80 % $\dot{V}O_{2\text{max}}$ is generally above the body’s anabolic threshold (12).

15. Participants ran while facing a video image of themselves projected on to the screen directly in front of them as they ran on the treadmill. Participants were instructed to pay full attention to the image throughout the experiment. They were informed that by using the handheld switch, they were to react as fast as possible to separate illuminations of individual LED stimuli that would appear intermittently on the screen in the lower arm and leg areas of the image. This manipulation served two purposes: first, to give some indication of the attentional demands as assessed through RT, and second to ensure that visual coupling with areas associated with phased limb
movement was maintained throughout each run. Following these instructions a heart rate monitor was fitted and briefings were given on the scheduling and duration of oxygen samples to be taken.

Experimental conditions

16. Each run was performed under one of three experimental conditions that differed only in the nature of the visual information available to the runner. The order of presentation of the conditions was counterbalanced across the sample group. There were two dynamic experimental conditions. The first required participants to run while watching live video feedback of themselves face-on, as would be the case when running in front of a standard mirror. The dynamic image provided concurrent feedback of limb movements that always appeared to be phased in symmetry (or 0° relative phase) with each participants’ limb movements while they ran. This condition was referred to as “Symmetrical”. Under the second condition participants ran while visually coupled with a mirror image of themselves reversed in the sagittal plane. The implications of this condition were that runners saw themselves face-on (as in a normal mirror) but their actions were reversed so that when they moved their right hand, for example, it was their left hand that moved in the image. Thus, limb movements in the image appeared to be phased in asymmetry (or 180° relative phase) with the participants’ limbs during running. This condition was referred to as “Asymmetrical”. In the control condition, participants ran while facing a static image of themselves. The static image was created by digitally editing video footage taken before experimental testing. A frozen image of each participant was recorded over a 25 min period and played back on the projection screen during the run. To avoid any distractions, the camera and projector were positioned so that the participants’ heads
were occluded from view on all three runs. In the interest of visual consistency, each runner wore the same clothes for each session.

Data analysis

17. Metabolic, kinematic, and psychological indices of performance ‘stability’ were obtained as detailed below. All vision conditions were analyzed using pre-planned orthogonal contrasts where first the static control condition was compared to the two dynamic conditions and then second the two dynamic conditions were compared to each other. Speed (i.e., slow and fast) and time were repeated measures factors in the majority of analyses. Due to the differential durations of each speed condition and variations across measures in terms of the number of data points collected, the time variable and the number of levels of this variable differed across measures as detailed below. When data points were missing for participants (due to experimenter or equipment error) the adjusted n value is reported for that measure, otherwise n = 10. Significant interactions involving vision were further analyzed using Tukey post hoc procedures. Significance was set at p < 0.05. Partial eta squared values are reported as measures of effect size.

Metabolic measures

Oxygen consumption

18. Samples of oxygen consumption (ml·kg·min⁻¹) were measured during performance at 60 % and 80 % $\dot{V}O_2\max$ for each of the three experimental runs. One min samples were taken during the 3rd, 6th, 9th, and 12th min of testing at the slow speed, yielding four data points. These means were compared in a 3 condition x 4 time period mixed ANOVA. At the fast speed, 1 min samples were recorded during the 17th and the 19th min, yielding two means. To enable statistical comparisons
across speed, only two means corresponding to the last two measures of the slow condition were compared to the two means at fast condition in a 3-way mixed ANOVA.

Heart rate

19. Heart rate (beats·min⁻¹) was recorded continuously. These data were averaged over 5 min periods yielding four mean data points (three slow and one fast). Two analyses were conducted on this data first comparing across the two speeds (last block at the slow speed) and then comparing across the three blocks in the slow speed only.

Rating of Perceived Exertion (RPE)

20. Participants indicated their perceived level of physical exertion using Borg’s (2001) scale for RPE at 3 min intervals after the start of each run. Participants called out the numeric rating they perceived as most representative of their overall (central and peripheral) level of physical exertion. The scale ranged from 6 – 20 (where 6 = no exertion at all, and 20 = maximal exertion). The 3 min scheduling provided six data points across the run (four at the slow speed and two at the fast speed). For statistical analyses, comparisons were made across four means corresponding to the last two blocks of the slow condition and the two means of the fast condition. A second analysis was conducted comparing across the four means for the slow condition only.

Kinematic measures

Standard deviation of footfall variability

21. Kinematic data were collected for 5 s capture periods at intervals of 2.5 min from the start of the run during performance at 60 % and 80 % $\dot{V}O_{2\text{max}}$. This analysis yielded six data points at the slow speed. Kinematics were captured every 1.5 min
from the start of the shorter duration fast condition, yielding three data points. Following data tracking, the data was exported using a Qualisys Track Manager (QTM) macro program named PCReflex into a Microsoft based application called Excelmr. These data were then filtered at 7 Hz using a dual-order Butterworth filter. Lateral and vertical displacement of the toe marker was calculated, as was the velocity of this marker in the vertical plane. Peak velocity was used to locate the point of toe strike within the gait cycle. The standard deviation of lateral displacement of the toe marker between full gait cycles across each capture period provided a measure of footfall variability. As in other analyses, variability was compared across the slow and fast speeds (based on the mean variability of the final three time points in each condition). A further analysis compared variability at the slow speed only as a function of time. Standard deviations based on the 1st, 2nd, and 3rd sample periods (at 2.5, 5 and 7.5 min respectively) were compared to those from the 4th, 5th, and 6th samples (at 10, 12.5, and 15 min respectively).

Footfall frequency

22. A common point in the gait cycle, as determined by the lowest value in the gait cycle for the right toe’s vertical (z) velocity was identified. Cycle frequency was then obtained by dividing the 5 s capture period by the number of completed step cycles within that time period. Similar analyses to those carried out for footfall variability were conducted.

Psychological measures

Reaction Time (RT)
23. Mean RTs were calculated over approximately 5 min intervals resulting in three
data points for the slow speed and one mean data point for the fast condition. Two
analyses were performed on this data as detailed for the other measures above.

Rating Scale for Mental Effort (RSME)

24. At 3 min intervals participants indicated their perceived level of mental effort
using the standardized RSME (30). Participants were presented with a scale and
asked to call out the numeric rating they perceived as most representative of the
mental workload they were experiencing (0 - 150, where 0 = absolutely no effort, and
150 = extreme effort). Measurements were scheduled to take place at 3 min intervals
from the beginning of each trial, resulting in four mean values for the slow condition
and two for the fast condition. The means of the first and last samples at the slow
speed were compared to the two means at the fast speed in a 3-way ANOVA with
repeated measures for speed and time block. A second analysis was performed on the
slow condition only comparing the four means.

Results

Metabolic dependent variables

Oxygen consumption

25. Mean $\bar{V}O_2$ data across the slow and fast conditions are presented in Figure 1. Pre-
planned contrasts comparing the dynamic conditions to the static condition, F(1,9) =
7.75, $p < .05$, $\eta^2_p = .46$, and the asymmetrical to the symmetrical condition, F(1,9) =
5.78, $p < .05$, $\eta^2_p = .39$, were both statistically significant. The dynamic conditions
were generally more economical than the static condition, but this was primarily due
to the lower $\bar{V}O_2$ consumption for the symmetrical versus the asymmetrical condition
($M = 37.46$, $SD = 6.49$ vs. $M = 39.02$, $SD = 6.88$ mL·kg·min$^{-1}$ respectively). Main
effects for both speed, F(1,9) = 170.91, $p < .001$, $\eta^2_p = .95$, and time, F(1,9) = 36.88,
were observed. The slow condition was more economical than the fast and the earlier time period showed lower 

\[ \dot{V}O_2 \] consumption than the later one. The only interaction effect was for visual condition and speed, \( F(1,9) = 5.34, p < .05, \eta_p^2 = .37 \) when comparing the static condition to the two dynamic conditions. The difference between the conditions was increased under faster speeds. Although similar trends were observed for visual condition at the slow speed, no significant differences were observed.

**Heart rate**

26. The mean heart rate data (n=8) showed that the lowest values were observed under the symmetrical visual coupling condition (see Table 1). However, there were no significant differences across the vision conditions when comparing across the two speeds (asymmetrical vs. symmetrical, \( F(1,7) = 2.43, p = .16, \eta_p^2 = .26 \)), or in the slow condition only (asymmetrical vs. symmetrical, \( F(1,7) = 2.39, p = .17, \eta_p^2 = .25 \)). The time effect was significant at the slow speeds, showing a significant linear trend for increased heart rate as a function of time, \( F(1, 7) = 114.25, p < .001, \eta_p^2 = .94 \).

**RPE**

27. There were no significant effects involving vision, although, as with the other physiological measures, there was a trend for the symmetrical condition to be perceived as the least effortful, particularly under fast speeds (see Table 2). The asymmetrical condition was perceived as the most effortful. Main effects for time for both the slow condition and when comparing across two subsequent blocks for the slow and fast condition, provided evidence of the typical effect of fatigue on level of perceived exertion, \( F(3, 27) = 24.22, p < .001, \eta_p^2 = .73 \) and \( F(1,9) = 25.46, p < .001, \eta_p^2 = .74 \), respectively. There was also a significant interaction across speed and time,
F(1,9) = 5.13, p = .05, $\eta_p^2 = .36$, showing that the perception of fatigue was more affected by time at the faster speed.

Kinematic measures

**Mean SD of lateral footfall variability**

28. At the slow speed there were no significant effects pertaining to vision condition (n = 6). However, when vision condition was compared across the two speeds a significant speed x vision interaction effect was observed. This effect was due to the difference in footfall variability between the dynamic and static conditions, F(1,5) = 10.20, p < .05, $\eta_p^2 = .67$. This interaction effect is illustrated in Figure 2. At the fast speed, the dynamic conditions (in particular the asymmetrical condition) were performed with more variability than the static, control condition.

**Gait cycle frequency**

29. Analysis of gait cycle frequency (n = 6) yielded a main effect of speed when comparing the last block of the slow speed to the fast speed, F(1,5) = 26.55, p < .01, $\eta_p^2 = .84$. There were no significant effects involving vision (see Table 3).

Psychological measures

**Reaction time**

30. Reaction time was slower under both dynamic conditions in comparison to the static condition, when comparing the RTs from the last block of the slow speed to the fast speed, F(1,9) = 6.80, p < .05, $\eta_p^2 = .43$. These data are illustrated in Figure 3. Vision did not interact with speed. For the slow speed condition, the difference between the vision conditions was not significant, despite a similar trend as detailed above, F(1,9) = 2.64, p = .14, $\eta_p^2 = .23$. 
31. The condition effects were not significant but there was a significant three way interaction across vision, speed, and time (n = 9). The asymmetric condition was rated higher for mental effort than the symmetric, dynamic condition (see Figure 4). This effect was significant at the fast speeds and in the last block, F(1,8) = 10.85, \( p = .01, \) \( \eta^2_p = .58 \). Significant effects of speed, F(1,8) = 72.06, \( p < .001, \) \( \eta^2_p = .90 \), and time, F(1,8) = 62.53, \( p < .001, \) \( \eta^2_p = .89 \), confirmed the prediction that the faster speed would require more mental effort than the slower speed and that perceptions of mental effort would be affected by time and interference (i.e., fatigue). A significant time effect was observed when comparing across the four time blocks at the slow speed, F(3,24) = 87.72, \( p < .001, \) \( \eta^2_p = .92 \).

Discussion

32. We examined whether treadmill running stability is mediated by incidental visual couplings with perceptual information. Stability was determined by examining various systems assumed to be reflective of coordination efficiency (i.e., metabolic, kinematic, and cognitive). In line with earlier research into between-person coordination (e.g., 19), it was predicted that incidental visual coupling with concurrent feedback of limb movements phased in visual symmetry with the body would afford a greater level of stability than asymmetrical limb movements or a static visual image. This stability was expected to be indexed through increased metabolic economy, reduced cognitive load, and decreased kinematic variability. Increases in metabolic demands, as a function of increases in both speed and time, were expected to accentuate any effects of the visual manipulations.

33. The vision conditions affected various measures of effort and stability of treadmill locomotion. Although the effects were not reliably observed across all
dependent measures, a trend was evident across variables for the asymmetrical, dynamic coupling condition to be perceived and measured as the most effortful and variable in comparison to the static condition and the symmetrical, dynamic condition. For measures of \(\dot{VO}_2\) consumption (mL·kg·min\(^{-1}\)) the symmetrical, dynamic condition resulted in a more economical performance than the control condition, supporting our original predictions. However, this effect was not observed for heart rate, or RPE. Moreover, the dynamic conditions generally resulted in slower RTs and increased variability in footfall when compared to the static condition, which would not unequivocally support a “stability enhancing” effect for unintentional, in-phase coupling.

34. Measures of \(\dot{VO}_2\) have been shown to differentiate across relative phase patterns in a bicycle ergometer task (11). These authors showed in-phase (i.e., symmetrical movements of the legs) to be more stable and accurate than anti-phase when examining displacement variability. Conversely, anti-phase was shown to be more economical. Lay et al. (11) indicated that dynamically stable coordination modes compete with metabolically economic modes. The results from our research extend these conclusions. Although participants in our study were always performing anti-phase movements, the visual-spatial constraints additionally impacted on the efficiency of this movement pattern, particularly at higher frequencies.

35. Being unavoidably coordinated with a symmetrical motion structure appears to afford a more economical running style when compared with asymmetrical and static conditions. In comparison to the asymmetrical condition, this type of symmetrical mirror coupling also feels less mentally demanding, as evidenced in the RSME data. In post experimental de-briefing participants also expressed ‘discomfort’ experienced under the ‘disorientating’ asymmetrical conditions, in comparison to the
‘less effortful’ symmetric and static conditions. One explanation for these findings might be in terms of a more relaxed running style afforded by the symmetrical coupling. Indeed, Caird, McKenzie, & Sleivert (7) have shown that participants who undertook psychological relaxation training prior to treadmill running were able to lower their heart rates by 2.5 % and decrease oxygen consumption by 7.3 % even though fitness levels did not change. However, as discussed later, the symmetrical coupling did not result in a more kinematically stable movement, which was initially expected to be indicative of a relaxed running style.

36. The above findings concur with research showing that visual scenes characterized by stimuli moving in the same direction (i.e., in-phase or isodirectional) are perceptually more salient than other motion structures (e.g., 4, 5, 16). According to the ‘isodirectional principle’, visual perception of limbs moving in the same direction enhances the stability of the in-phase pattern, whereas perception of limbs moving in the anti-phase pattern reduces the stability of relative phase patterns (5). Furthermore, perceived variability in 180° mean relative phase increases as a function of movement frequency, while perception of 0° mean relative phase does not change as frequency increases (28).

37. Despite the metabolic differences between conditions, the kinematic data did not show evidence of enhanced stability when participants were symmetrically coupled. Indeed, the control condition appeared to be the most stable. One explanation for this finding may lie in the RT data. Responding to LED stimuli in the dynamic displays was arguably a more difficult task than under static conditions as the moving images would make stimuli detection more difficult. The cognitive demands associated with the RT task for the dynamic displays would make any clear
comparisons with the control condition difficult. In fact, because of the secondary
task effects associated with the RT task, it is an even more telling result to find \( \dot{V}O_2 \)
advantages for the dynamic conditions.

38. In conclusion we have shown perceptual-spatial manipulations can affect
various indices of stability during treadmill running. While predicted effects were not
reliably found across all measures, there is evidence to support the conclusion that
treadmill running is more efficient when viewing mirror-like images of symmetrical
limb movements. Our findings highlight the complex interactions between motor and
perceptual constraints, yet further research is required to better understand the
energetic costs associated with incidental visual couplings and what might be the
‘preferred’ state. It is possible that advanced understanding of these issues could
inform practical applications of training and motor performance across domains. Our
data indicate that treadmill running in front of a mirror, as is common in a gym,
induces a more economic running state. For some people (such as the elderly) this
might be desirable, but for others, running in front of a mirror might not deliver the
physiological demands required in a training session. On the other hand, runners may
find it beneficial to utilize these perceptual affordances to conserve energy while
running in synchrony behind a competitor in a race.

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