Summary

Anchoring: moving from theory to therapy  Melvyn Roerdink

Limb movements are often rhythmic in nature, exhibiting sinusoidal-like oscillations. Nevertheless, the ‘back and forth’ trajectories are seldom perfectly harmonic and symmetric but often show discrepancies between the two half cycles, for example in terms of differences in peak velocity, fluency, and local reductions of spatial variability. A central tenet of the notion of anchoring, as advanced in coordination dynamics, is that such kinematic differences are informative about the underlying control and the prevailing informational, musculoskeletal, and intentional constraints that influence the way in which movements are coordinated. In particular, points or regions of reduced variability have been interpreted to serve as control or anchor points for the complete movement cycle. The work reported in this thesis examines the combined effect of informational and musculoskeletal constraints on anchoring and seeks to translate these insights to clinical applications. A series of studies on rhythmic unimanual visuomotor tracking (Chapters 2-4) and auditory-motor coordination (Chapter 5) are reported aimed at uncovering the informational and musculoskeletal underpinnings of anchoring. These fundamental insights motivated two further studies, by way of spadework for therapeutic applications, of the effects of acoustic cues on gait coordination (Chapters 6 and 7), which in turn motivated the development of an instrumented treadmill for movement-dependent visual and acoustic cueing in a rehabilitation setting (Chapters 8 and 9).

The first experiment, presented in Chapter 2, examined the effects of correct and transformed visual feedback on tracking performance (accuracy and stability) and visual search behavior in unimanual rhythmic visuomotor tracking. The results indicated that tracking performance was aided by visual feedback manipulations resulting in coherently grouped (i.e., in-phase) visual motion structures. Visual search patterns revealed that smooth pursuit eye movements only occurred at lower oscillation frequencies while at higher frequencies gaze was typically fixated at a specific location. Gaze fixations at the endpoints were accompanied by reduced motor variability at
those locations, reflecting a form of visuomotor anchoring that may support
the pickup of discrete information as well as the control of hand movements
to a desired location.

Chapter 2 revealed clear instances of visuomotor anchoring with
marked effects of gaze direction but also hinted at a musculoskeletal
contribution to anchoring (i.e., through systematic shifts in wrist position
between feedback and no feedback conditions), even though neither of these
factors was varied explicitly. Chapter 3 reports an experiment aimed at
delineating the effects of visual and musculoskeletal factors on anchoring
behavior in visuomotor tracking, as well as their relative contributions and
interrelations. Anchoring was affected by both factors in the absence of any
significant interactions, implying that their contributions were independent.
As in Chapter 2, anchoring depended on gaze direction. In addition, when
the wrist was in a flexed (extended) posture endpoint variability was smaller
for the flexion (extension) endpoint than for the extension (flexion)
endpoint. Detailed analyses of the tracking trajectories in terms of velocity
profiles and Hooke’s portraits showed that the tracking dynamics were
affected more by wrist posture than by gaze direction. The processes
underlying the observed independent effects of gaze direction and wrist
posture on anchoring were explored further in Chapters 4 and 5,
respectively.

The study presented in Chapter 4 aimed to unravel the informational
basis of anchor points in rhythmic visuomotor tracking by dissociating
between information about the spatial location of a particular movement
reversal point and/or information about the precise timing of a movement
reversal point, both picked up at the foveated endpoint. The relation between
target-related timing information picked up at the foveated endpoint and the
required timing of the hand movement were uncoupled by inviting
participants to track an oscillating target signal in antiphase. The relative
contribution of the two sources of information to anchoring was examined
by comparing the variability of foveated and non-foveated endpoints. Both
gaze anchoring and perceptual-motor anchoring were evident, respectively
implying that gaze and hand movements were co-aligned and that
movements were steered to a particular endpoint based on target-related timing information. This finding has direct implications for understanding the differential stability of rhythmic in-phase and antiphase unimanual visuomotor tracking in that these sources of anchoring are operative at the same endpoint in in-phase coordination and at separate endpoints in antiphase coordination.

In Chapter 5 the relative contribution of musculoskeletal (wrist posture) and informational (acoustic pacing) mediators of anchoring were delineated. The musculoskeletal mediators outweighed the informational ones in that musculoskeletal anchoring effects were more prominent when musculoskeletal and informational anchor points were in conflict (e.g., extend-on-the-beat with the wrist flexed). Furthermore, a bias to anchoring on peak flexion (extension) in the double pacing condition was observed with the wrist flexed (extended), presumably because in this situation informational and musculoskeletal anchor points coincide. Where anchoring occurs in the movement cycle depends on the net additive effects of the musculoskeletal and information mediators of anchoring. Anchoring was not only assessed in terms of movement kinematics but also in terms of concomitant muscular activity, corroborating again the independence of musculoskeletal and informational mediators of anchoring.

The potential of anchoring for practical applications was explored in Chapter 6, where the efficacy of acoustically paced treadmill walking as a method for improving gait coordination in stroke patients was examined. As in Chapter 5, acoustic stimuli served as informational mediators for anchoring, albeit in this case for footfalls. Stride frequency was adjusted to different acoustic pacing frequencies in both stroke patients and healthy elderly while stroke patients’ gait symmetry improved with acoustic pacing. These results suggested that acoustically paced treadmill walking provides an effective means for immediately modifying stride frequency and improving gait coordination in people after stroke and may therefore be usefully applied in physical therapy. Although acoustic stimuli were presented for left and right footfalls, analyses of auditory-motor coordination revealed that stroke patients predominantly coordinated the footfalls of the
non-paretic limb to ipsilateral beats. Apparently, this is the most efficient way for stroke patients to deal with their gait asymmetry while being prompted to time their footfalls to (symmetric) acoustic signals.

Chapter 7 aimed to gain further insight into footfall anchoring to the beat of the metronome in acoustically paced treadmill walking following stroke. Different configurations of acoustic pacing were provided: no pacing, bilateral pacing (beats for both footfalls, as in Chapter 6), beats for paretic footfalls only, and beats for non-paretic footfalls only. Most stroke patients were able to synchronize their gait with the metronome in all configurations, with the coupling between beats and footfalls being stronger with bilateral pacing. Likewise, responses to rhythm perturbations were quicker with bilateral pacing, albeit only significantly so for healthy controls. Thus, in gait rehabilitation practice, the use of acoustic rhythms may be more effective when both footfalls are paced. In addition, detailed examination of recovery characteristics following perturbations revealed that stroke patients had difficulty in accelerating their pace to restore synchronization, as evidenced by a large number of atypical slower-step responses to beats occurring earlier than expected. Therefore, rhythm perturbations during acoustically paced treadmill walking may not only be employed to evaluate the stability of auditory-motor synchronization but also to train and evaluate gait adaptations in rehabilitation.

Chapters 6 and 7 demonstrated the efficacy of cueing in pathological gait. These and related methods of clinical gait training may benefit from movement-dependent event control, that is, technical applications in which events such as acoustic cueing or obstacle appearance are (co)determined online by gait properties. A prerequisite for successful gait-dependent event control is accurate online detection of gait characteristics such as heel strike. In Chapter 8 the feasibility of online heel strike detection from center-of-pressure profiles using a single force platform embedded in a treadmill was assessed. Good correspondence was achieved between online heel strike detections using center-of-pressure profiles and those derived offline from kinematic data as well as between spatial and temporal gait parameters. These positive results warrant implementations of gait-dependent event
control based on online center-of-pressure pattern recognition, such as acoustic and visual cueing.

The final chapter provides a summary of the main findings of the work presented in the thesis and a discussion of their theoretical and practical implications. The original definition of anchoring was broadened by recognizing that, besides task-specific information, anchoring may also result from the exploitation of task-specific musculoskeletal properties to improve task performance and economy. Informational, musculoskeletal, but also intentional factors were found to be major and independent mediators of anchoring. Collectively the results indicated that anchoring locations are not fixed in the perceptual-motor workspace but depend on prevailing cost functions such as task performance/stability (more anchor points may be better) and task economy/attentional burden (less anchor points may be better). The compatibility of the notion of anchoring with related concepts like gaze anchoring, event timing, and Betonung are discussed within the context of Pressing’s theory of referential dynamics. Besides theoretical advancements, the adopted translational approach also led to emerging insights for the use of external rhythms in gait rehabilitation following stroke. Those rhythms may not only be used to improve the gait coordination of stroke patients, most notably its asymmetry, but also to modulate gait by changing the metronome rate and assess gait adaptability by rhythm perturbations. The second part of the epilogue describes the further development of the instrumented treadmill into a rehabilitation tool for gait evaluation and clinical gait training. This tool may facilitate gait interventions based on anchoring in clinical practice and several directions for future clinical applications and research are proposed for moving from theory to therapy.