Follow the Leader

The Role of Local and Global Visual Information for Keeping Distance in Interpersonal Coordination

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Abstract

Despite many years of research into human movement, how humans deal with information in dynamical situations is still subject to debate. The current research programme examined an individual’s ability to coordinate their actions with others in invasion sports (‘interact-ability’) using the ecological dynamics theoretical framework to address this general aim. In its essence interact-ability describes how humans make sense of their sensory world in order to tie in - some form of - action output to serve goal-directed behaviour. A series of experimental studies examined the law-like relationship between agent and environment (cf., perception-action) when one has to coordinate with others. A virtual reality task was chosen that involved maintaining distance in locomotion: follow the leader.

The first study examined whether optical expansion by itself would enable distance keeping in a follow-the-leader locomotion task in forward-backward direction. In one condition, participants coordinated their locomotion with an expanding and compressing sphere, whilst in another with a fully animated avatar (i.e., with moving limbs). The coordination of the follower with the leader was analysed using response times (RT) and the point-estimate relative phase (\(\phi\)) to quantify the temporal synchrony. Additionally, the spatial accuracy was estimated by testing to what extent the rate of change in visual angle was nulled over time. Findings showed a decreased temporal synchrony, but no significant decrease in spatial accuracy, when no limb movement was present in the leader stimulus (i.e., sphere compared to avatar). Additionally, it appeared that regulating distance based on global motion information was affected by a direction-based visual angle bias. The second study then investigated if information for action could be situated along a spectrum from local (i.e.,
segmental) to global (i.e., expansion-compression) visual information sources. It also was examined how the perception-action coupling was mediated by key task constraints (i.e., regularity and viewpoint). Extending the analysis procedures of the first study, the virtual distance between follower and leader was estimated to further quantify the spatial accuracy. It was put forward that followers may benefit most from flexibly switching between information sources governed by task constraints. Participants followed more irregular leaders better when local motion information was available. Although information for action may not be easily situated along a linear spectrum, various relative benefits were put forward for each component of the proposed spectrum. In the third and final study, these follower-leader dynamics were examined in a lateral follow-the-leader task. It was shown that a point-light display provided information to tighten the temporal synchrony. However, as the spatial accuracy was not significantly affect by the information presented, it may be that early responses were as often facilitating as detrimental for keeping distance. Overall, this body of work may contribute towards understanding how action and perception are linked in dynamic interpersonal situations. Local sources of information were shown to contribute to a tightened temporal synchronization and global sources of information were consistently shown to provide pertinent distance-related information. The main contribution is substantiated by showing how agents in a whole-body interaction task can flexibly use different sources of information and do so as a function of task constraints.
Acknowledgements

This research project could not have come together without the help of many great colleagues and friends. First, I would like to thank Chris Button who has been an extremely supportive supervisor, all the way throughout my research. You gave me the freedom I needed to develop my ideas. You taught me how to strike that balance between perfection and productivity. By allowing me to find my own way through the many opportunities, distractions, hurdles, challenges and of course joys the PhD journey provides, I have had an incredibly rich experience.

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Publications and Presentations Related to this Thesis

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When I started this project, I could not have imagined the breadth of this research experience. Fascinated by the immense diversity and flexibility of interpersonal coordination, I set out to discover how individuals skilfully interact with others. Elite athletes often stand out due to key physiological (e.g., strength, speed or agility) and anthropological characteristics (e.g., height, in basketball). Additionally, elite athletes often appear to have an ability to seemingly operate in slow-motion, and make split second decisions that lead to successful performance. I have proposed the term of this skill ‘interact-ability’. I quickly realised that ‘studying’ this skill was not straight-forward. I have approached fundamental motor control research as a good starting point for studying interact-ability. This thesis is the summation of my learning so far.

This thesis starts by providing an overview of the literature. Through the work of Gibson, Brunswik and Barker I briefly describe the theoretical foundations upon which the framework of this research is based. Then, I narrow the focus to (skilful) perception and action. At the end of the literature review I provide a more detailed overview of the experimental studies that were part of my PhD programme.

In the subsequent chapters, I present the three experimental studies in which I have examined follow the leader coordination in a virtual reality task. This set of studies is unique in that I have examined whole-body movement responses to manipulated visual information in order to understand the role of the information presented. The first study is on the use of visual angle related information for maintaining distance. Based on results of the first study, I then investigated if information for action could sit on a spectrum from local to global motion information. Finally, in the third study I have considered the principles of this spectrum in a lateral follow the leader task. Lastly, in the overall discussion implications of the findings of each study are put forward.
This thesis provides insight into what role different sources of visual information play in interpersonal coordination. At a fundamental level these studies highlight that agents flexibly attune to the optimal source of information available. After undertaking this project, understanding the true nature of interpersonal coordination and its complexity will be the direction of my research going forward.
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<th>Symbol</th>
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<tr>
<td>$\alpha$</td>
<td>The visual angle as determined from an observer’s eyes</td>
</tr>
<tr>
<td>$\dot{\alpha}$</td>
<td>The rate of change of the visual angle as a result of changes in distance</td>
</tr>
<tr>
<td>$\tau$</td>
<td>‘Tau’ directly specifies time-to-contact based on the visual angle and its rate of change $\tau(t) = \alpha(t)/\dot{\alpha}(t)$</td>
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<tr>
<td>F2F</td>
<td>‘Face-to-face’, the viewpoint in which the leader is projected</td>
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<tr>
<td>F2B</td>
<td>‘Face-to-back’, the viewpoint in which the leader is projected</td>
</tr>
<tr>
<td>$CD$</td>
<td>‘Constant deviation’, reduction of time-series data to inform about the lead-lag relationship.</td>
</tr>
<tr>
<td>$VE$</td>
<td>‘Variable error’, reduction of time-series data to inform about the variability – and as such stability – of the lead-lag relationship.</td>
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<tr>
<td>$AD$</td>
<td>‘Absolute deviation’, reduction of time-series data to inform about the accuracy of the lead-lag relationship.</td>
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<tr>
<td>$\nu$</td>
<td>Velocity</td>
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<tr>
<td>$\delta$</td>
<td>Estimation of the relative virtual distance</td>
</tr>
<tr>
<td>$IAD$</td>
<td>The ‘inter-actor distance’</td>
</tr>
<tr>
<td>$RT$</td>
<td>Response time</td>
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<td>$\varphi$</td>
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Chapter 1
Overview of the Literature
1.1 Introduction

In sports, the best in their discipline will capture the amazement of many. When watching invasion sports like basketball, football, or rugby, one fascinating aspect is the ability of an individual player to exploit a situation (e.g., the position of the opponents, a teammate’s anticipation of a pass) in such a timely manner that the opponents are defeated and a teammate is given a scoring opportunity. Sometimes this happens in such a way that the outcome almost requires a slow-motion replay to understand how it happened. This skill or competence, wherein an individual interacts with its environment (or, more specifically, other players) has been termed the ‘interact-ability’ (Meerhoff & De Poel, 2014). Although interaction skill can speak to the imagination, it has proven difficult to research objectively as it combines many fields of science and therefore requires a clear theoretical framework. This overview of the literature provides the theoretical framework within which the research questions and research methods for this thesis have been developed. First, the adopted theoretical foundations will be addressed, and then it is highlighted through recent research what (visual) information may be used for action. Subsequently, the foundations and research examples are linked to what might be entailed in skilful interacting (i.e., interact-ability). Finally, the rationale behind the main task vehicle for this thesis – a follow-the-leader task – is set out.

1.2 Theoretical foundations

In the second half of the 20th century a field of research emerged that focused on the science of human movement. The central theorem became the proposition by Bernstein (1967) of the ‘actual’ challenge in movement science: how can a multivariable system – the human body with its countless degrees of freedom – be reduced to small enough components that it can actually be controlled? Over the years, many approaches have arisen that aimed to increase our understanding of this challenge. Neurophysiological approaches have developed our comprehension at the level of motor-units (Buchtal & Schmalbruch, 1980) and mirror-neurons (Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Rizzolatti et al., 1996). Behavioural approaches have helped develop an understanding of motor control (R. A. Schmidt, 1975), skill acquisition (Reed, 1988) and the coupling between perception and action (Bootsma & van Wieringen, 1990; Savelsbergh, Whiting, & Bootsma, 1991; Schöner, Dijkstra, & Jeka,
Movement sciences have become a multidisciplinary research field combining (evolutionary) biology, psychology, biomechanics and neuroscience. Recently, it has been suggested that an ecological dynamics framework (see Section 1.2.3) provides considerable explanatory power based on functional interactions between agents and their environment (Araújo, Davids, & Hristovski, 2006; Carson & Kelso, 2004; Chow et al., 2006; Davids, Glazier, Araújo, & Bartlett, 2003; McGarry, Anderson, Wallace, Hughes, & Franks, 2002; Vilar, Araújo, Davids, & Button, 2012). This approach combines ecological psychology and complex – or dynamical – systems. Ecological psychology emphasizes the intrinsic coupling between an actor and its environment (i.e., all that surrounds and potentially influences the agent). Arguably, the most important aspect for movement science according to ecological psychology is the coupling between perception and action. A complex system derives its complexity from interactions between the components of which it consists and the dynamical systems approach provides mathematical tools capture how these interactions emerge. Combined as the framework of ecological dynamics, this provides a good starting point to consider interact-ability. In a somewhat chronological order, the following sections will address the key aspects of ecological psychology and complex dynamical systems.

1.2.1 Ecological psychology

1.2.1.1 Brunswik’s roots

Ecological psychology finds its roots for a large part in Brunswik’s work on ecological validity. Brunswik (1943) set out to discuss the correlation between a proximal (subjective perception) and distal (objective characteristic) stimulus (Brunswik, 1943). Brunswik was a strong advocate of what was termed representative experimental design, which is rooted in the concept of probabilistic functionalism (Brunswik, 1955a, 1955b): a statement based on a sample (e.g., a group of subjects) from a population is only generalizable outside of that population to the extent to which the probabilistic functions have been accounted for in the sampling procedure. Representative design focuses on the generalizability of research findings to settings which are inevitably different from the settings in which the research was conducted. A radical standpoint is that any two different situations are never the same. Therefore, it should be established what elements are likely to influence the generalizability and control for these situations as much as possible. In the end, any scientific undertaking is only as valuable as its appreciation of the limits of its generalizability. The generalizability of
research findings is limited to the extent to which pertinent variables have been accounted for (e.g., by randomization) in the experimental design. Brunswik put forward the notion of randomizing both person-subjects (participants) and person-objects (models). Arguably, representative design is not limited to randomization of participants and models, but can be applied to any of the aspects of coordination that (may) have a functional influence on the studied behaviour (see Section 1.2.1.3). As will become clear throughout this chapter, for the current thesis the most important aspect of the studied behaviour is the coupling between perception and action. Therefore, the methodology adopted in this thesis will ensure a representative coupling between perception and action.

1.2.1.2 Environment-actor system

The philosophers R.G. Barker (1968) and J.J. Gibson (1979) played an important role in further developing the field of ecological psychology. Barker advocated that “a task of ecological psychology is to discover how properties of the person and the properties of the environment are related, in situ” (Barker, 1968, p. 158), referring to the difference between subjective observations and objective characteristics. Gibson expanded upon this viewpoint by re-formulating the commonly held perception that “the laboratory can never be like life” as “the laboratory must be like life!” (Gibson, 1979, p. 3). Gibson made this radical statement to set the tone in the debate in ecological psychology about representative design. In the core, Gibson argued representative design extended beyond observing ‘natural’ behaviour. Instead, Gibson shifted the emphasis towards designing experiments that effectively addressed the studied behaviour. Clearly, for the traditional positivist approach this is a radical and challenging point of view. Rather than emphasizing that research in a laboratory is not generalizable outside the laboratory, Gibson here emphasizes that it is always generalizable, but not indiscriminately. Gibson subsequently proposed the ecological approach to visual perception as a guide to discovery, a framework crucial for (ecological) psychology to maintain its scientific integrity. Ecological psychology inspired a re-interpretation of how perception is generated by circumventing the objective-subjective paradigm with direct perception of affordances and the subsequent conceptualization of the environment-actor system (Bootsma, Fayt, Zaal, & Laurent, 1997). The actor refers to the organism, performer, person, athlete or agent that forms a subsystem of a larger system. The environment is anything that surrounds the actor and may influence its behaviour or vice versa (e.g., a door handle, traffic, the boundaries of a sports field, or even other actors). By functionally linking
the objective (environment) and subjective (actor), perception becomes direct. When embedding perception in a functional basis, (the accuracy of) an objective truth becomes redundant. Instead, one only needs to perceive the environment in order to be able to functionally couple it to the intended actions. Gibson proposed the outside world is perceived in terms of affordances, which neatly illustrates how perception can be functionally linked to behaviour. These are opportunities for action provided by the environment relative to the actor (see Section 1.3.2.1). Note that Brunswik’s idea of perception was deeply rooted in the dichotomy between the objective and the subjective; therefore, the jump to Gibson’s perception of affordances was in fact inherently contradictory of Brunswik’s ideas on perception (Vicente, 2003). In sum, Barker’s school of ecological psychology represents how variables for perception are dictated by the relationship with the environment (which is why it is also referred to as environmental psychology), while Gibson’s philosophical approach puts forward how perception may be situated in the relationship between the actor and its environment.

1.2.1.3 Ecological psychology in human movement

In essence, the connectedness between actor and environment (cf., environment-actor system) suggests that studying an actor’s behaviour is only directly relevant in relation to that specific environment. This means that even though strictly speaking all behaviour is ‘natural’ behaviour, the representativeness of the context determines how generalizable the observations are. Thus, when systematically observing – or manipulating – behaviour, it is crucial to incorporate a representative design (Brunswik, 1956; Dicks, Davids, & Button, 2009). To adequately address interpersonal coordination, the environment-actor system must somehow remain representative. A representative design should allow the exploitation of the perceptual system similarly to typical interactions with the environment (Hammond & Stewart, 2001). For example, in the field of motor control, numerous studies have shown that interpersonal coordination is affected when the environment-actor system is modified (e.g., Araújo, Davids, & Passos, 2007; Araújo, Davids, & Serpa, 2005; Davids, Bennett, & Button, 2002; Dhami, Hertwig, & Hoffrage, 2004; Dicks et al., 2009). In a study on anticipating kicking direction by goal-keepers in penalty kicks, Dicks et al. (2009) found that responses were substantially different when participants had to anticipate kicking direction by simply pressing a button, compared to indicating the direction by physically diving to intercept the ball. In this example, physically moving is a functional part of the observed process.
(perception of kicking direction) and should therefore be accounted for in the experimental design in order to adhere to the tenets of representative design. To be accurate, this does not mean that either behaviour is ‘natural’ or ‘unnatural’, it merely means that when intending to say something about the perception-action coupling for a certain task, its applicability is restricted to similar settings as the task was performed under.

One potentially useful tool for studying human movement in a setting that allows a strong perception-action coupling (see Section also 1.3.2) has become available through recent technological developments: virtual reality. A virtual environment serves to realistically simulate a (visual) reality that is different from the actual reality and only exists virtually. Most commonly, virtual reality encompasses simulation of a visual virtual reality. It is also possible to include a simulation of an auditory and even proprioceptive virtual reality (Gokeler et al., 2014). Virtual reality allows for maintaining an accurate representation of many movement-related tasks, although it is not automatically representative. Stoffregen, Bardy, Smart, and Pagulayan (2003) argue that by merely being aware of acting in a virtual world behaviour is already affected. This may be of concern when aiming to design truly representative experiments, however – particularly given the accelerating technological developments – virtual reality can be an important tool for ecological psychology (Tarr & Warren, 2002). For the purpose of the current thesis, virtual reality can be used to create an environment-actor system that can be completely controlled without breaking the connectedness between environment and actor, or perception and action¹. Most notably, in a virtual reality setting the available information can be manipulated as governed by the research questions (e.g., Kelly, Donaldson, Sjolund, & Freiberg, 2013; Stone et al., 2014). In sum, it can be argued that virtual reality may provide an excellent research tool for studying human movement, as long as its limitations are taken into account (Varlet et al., 2013; Watson et al., 2011).

¹ Although virtual reality provides clear advantages for the methodology adopted in this thesis, it needs to be emphasized that from a strict ecological perspective it can never be ruled out that key aspects of the perception-action coupling may be affected by the virtual display. This does not influence the pertinence of the research findings, however, it does imply that generalizing to person to person scenarios needs to be done with care.
1.2.2 Complex dynamical systems

1.2.2.1 Intra- and inter-personal coordination

From the previous sections it can be inferred that isolating components to understand multicomponent systems may be problematic given the intricate links within the environment-actor system. Similarly, Turvey (1990) points out that coordination cannot be explained by models specific to individual phenomena. According to Turvey, Bernstein’s problem of control calls for a “new strategy characterized by a search for general explanation and an appreciation of the similarities between coordination and other natural phenomena in which multiple components become collectively organized” (Turvey, 1990, p. 941). Turvey therefore advocated for adoption of a dynamical systems approach to understanding human movement. A dynamical system consists of multiple interacting subsystems and functions without a central controller. Individual subsystems of a complex system can act on local rules and do not necessarily have information (or even ‘awareness’) regarding system organisation as a whole (Herbert-Read et al., 2011; flocking birds, schools of fish or perhaps even humans in a crowd; cf., Hildenbrandt, Carere, & Hemelrijk, 2010; Moussaid, Helbing, & Theraulaz, 2011). As such, the dynamics (i.e., behaviour or coordination) emerge from the interactions between the components of which the system consists. Although human behaviour certainly is not merely governed by processes of which the individuals are unaware, complex behaviour (e.g., movement systems) can be described in terms of its interacting subsystems (e.g., motor units, muscles, limbs, actors; Araújo, Davids, et al., 2006; Araújo, Passos, & Davids, 2006; Davids et al., 2003; Glazier, Davids, & Bartlett, 2003).

For within person coordination, it was found that two oscillating joints linked by some form of information exchange (i.e., the auditory cues of a metronome) showed accurately predictable coordination patterns based on mathematical models (e.g., the HKB model, see Haken, Kelso, & Bunz, 1985). These pioneering models led to the pursuit of finding other law-like relationships across other aspects of human coordination (Turvey, 1990). Bimanual coordination was the first movement system to which the tools from the dynamical systems theory were applied. Kelso (1984) focused on the bimanual coordination task of wiggling hands in in- or anti-phase coordination (i.e., in synchrony or with a half-cycle delay). The hands can be described as coupled oscillators, which adhere to robust and repeatable organizational principles (e.g., attractor and repeller states, order and control parameters).
These principles describe how coordinative patterns can emerge and arguably explain how complexity may be embedded in these lawful relationships. For human movement science bimanual coordination serves as a crucial stepping stone to explore these coordinative principles that eventually may be able to explain many complex forms of coordination (e.g., interpersonal coordination). In bimanual coordination it was for example studied how a control parameter (e.g., movement frequency) can influence the order parameter (i.e., mode of coordination) by inducing phase shifts (i.e., an abrupt change in the mode of coordination). As such, bimanual coordination has provided a powerful example of how non-linear characteristics of coordination can be explained using tools from dynamical systems. Note that for the case of bimanual coordination, the coupling between components consists of the neural (or mechanical, or perceptual) pathways within the actor (Mechsner, Kerzel, Knoblich, & Prinz, 2001), but other observations suggest the applicability of these law-like phenomena to between actors. Two oscillating components can become entrained if they are coupled. The phenomenon of entrainment refers to the universal trend of coupling between two or more rhythmic units (oscillators). This can refer to two pendulum clocks hanging on a wall (as observed as early as 1655 by Huygens), synchronously chirping crickets, synchronously flashing fireflies, neural networks, or the spinal cord that controls rhythmic behaviours such as breathing, running and chewing (Pikovsky, Rosenblum, & Kurths, 2003; Strogatz & Stewart, 1993).

Given its usefulness as a research tool for bimanual coordination, these universal principles have been extended to coordination between people (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; R. C. Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; R. C. Schmidt, Carello, & Turvey, 1990). The coupling between people is mostly visual (or auditory), rather than mechanical. For example, crowds clapping in unison have the tendency to synchronize their clapping rhythm without the intention of doing so (Neda, Ravasz, Brechet, Vicsek, & Barabasi, 2000). R. C. Schmidt et al. (1990) showed that these principles were indeed applicable to interpersonal coordination. In their experiments, R. C. Schmidt et al. (1990) let two people watch each other’s swinging lower leg. By simply paying attention to the other person’s leg, the legs become entrained. Furthermore, as the leg swing frequency increased, the authors observed that phase shifts occurred similarly as with Kelso’s bimanual coordination. Arguably, their instructions, in which they suggested that phase shifts might occur and were allowed, already affected coupling behaviour, as the participants may have been primed to think about these changes in coordination. These phase shifts are of high
importance as it underlines how coordination can be organized through the interactions of the components, rather than central governance. This may imply that the similar organizational principles apply for oscillating hands within a person and for oscillating legs between persons. Clearly, in many situations the inter-agent coupling yields synchronization tendencies (R. C. Schmidt & Turvey, 1994).

Even more remarkable is that this process was not only evident in goal-directed intentional coupling, but also in unintentional coupling. That is, without the intention to synchronize movements there are many tasks during which people become unintentionally coupled. For example, when two people start to walk in the same rhythm while walking next to each other (Nessler & Gilliland, 2009; van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008). Richardson, Marsh, and Schmidt (2005) showed that both with and without the intention to synchronize movement, swinging handheld pendulums resulted in interpersonal synchronization (i.e., entrainment). Richardson et al. (2007) have since demonstrated that these unintentional synchronization tendencies also occurred when people are asked to rock chairs next to each other. Marmelat, Delignières, Torre, Beek, and Daffertshofer (2014) examined whether following a person can influence the locomotion pattern. It was found that even the gait variability, which is rather individual-specific, can be influenced through coupling visually to another person walking. Nessler and Gilliland (2010) showed that walking side-by-side encourages the adoption of natural (cf., more optimal) patterns of locomotion and proposed that this may facilitate rehabilitation after injury. Additionally, they noticed that this effect is stronger when participants actively attempted to synchronize compared to when participants became entrained unintentionally when walking side-by-side.

In fact, if the coupling between people is strong enough, even a complex pattern more typically used by other animals, such as trotting, can be observed. Complexity emerges when two components influence each other to become coordinated. Harrison and Richardson (2009) experimented with how people’s leg movements become spontaneously entrained when walking behind each other, forming either a phase-locked (i.e., stable) ‘trotting’, or ‘pacing’ pattern. A pacing pattern is where both participants move their right (or left) legs simultaneously, whereas a trotting pattern is where one moves their right whilst the other moves their left leg. In one condition this coupling happened whilst the actors were strapped together by a foam appendage (thus inducing a strong mechanical coupling). Furthermore, even when participants were not strapped together (coupling solely based on visual
information) phase-locking occurred, surprisingly only in a pacing pattern. It is likely that, the rear participants in the dyads managed to attune to the steps of the front participants in a way that the chance of a collision was lowest. Harrison and Richardson (2009) conclude that it is the lawful coupling between perceptual-motor systems that allows for complex patterns, like pacing or trotting locomotion, to emerge.

However, intrapersonal dynamics should be translated to interpersonal dynamics with caution (Marsh, Richardson, Baron, & Schmidt, 2006). Not all dynamical principles from theoretical models (for example the HKB-model) necessarily apply to interpersonal coordination dynamics. For example, van Ulzen et al. (2008) found that for interpersonal coordination of gait patterns, in-phase and anti-phase coordination were equally stable. Additionally, no systematic effects of increased velocity were found on stability of the coordination. These deviations from the original model can possibly be explained by a stronger influence of agency in between-person coordination. It was found by Meerhoff and De Poel (2014) that role-taking has a strong influence on the interpersonal coordination dynamics. In their experiment it was shown that the coupling between people was not symmetrical, that is the agents did not contribute equally to the dyadic coordination. This asymmetry in coupling may be important for interpersonal coordination and was even argued to form the basis of individual skill differences in interact-ability.

Overall, these studies suggest that application of any models of interpersonal coordination need to incorporate further aspects such as non-linearity and asymmetry that may exist between components of the system. The research on interpersonal coordination requires alternative, more flexible explanations of coordination between components than intrapersonal coordination. Coordination of a common, stable, yet adaptive motor skill like walking might actually be influenced by more than just the general laws of coupling. In sum, it can be said that (visual) coupling has a strong fundamental influence on coordination of interpersonal walking. Pertinent for such interpersonal coordination, approaching coordination as a complex system can indeed facilitate an understanding of the interactions between subsystems.
1.2.2.2 Applications of interpersonal coordination

Interpersonal, or perhaps more broadly inter-agent, coordination is a common occurrence in daily life. An agent is an entity with some level of agency, that is, the ability to act independently. By doing so, multiple agents can easily form complex patterns as each entity can influence the other and vice versa. In some cases, these complex patterns may be largely explained through complex dynamical systems. Buhl et al. (2006), for example, discuss how locusts can become coordinated as a group of ‘marching’ agents. For humans, sports provide interesting settings through which inter-agent coordination lead to the formation of complex patterns (Vilar, Araújo, Davids, & Bar-Yam, 2013). Given the promising developments for understanding dynamical systems, the tools of dynamical systems have been proposed to be used for studying interpersonal coordination in sports (R. C. Schmidt, O’Brien, & Sysko, 1999). McGarry et al. (2002) suggest that the same dynamical principles found in within-person coordination are indeed universal and apply to both one-versus-one and many-versus-many sports situations.

Regular movement patterns of actors – or groups of actors – emerge from the many organisational possibilities that exist in, for example, basketball, tennis, rugby union and soccer (Bourbousson, Seve, & McGarry, 2010a, 2010b; Palut & Zanone, 2005; Passos et al., 2008; Vilar, Araújo, Davids, & Travassos, 2012, respectively). In fact, sports teams have been described as superorganisms emphasizing how complex emergent collective behaviour may be a result of repeated interactions between individuals or subgroups forming a functional integrated superorganism (Duarte, Araújo, Vanda, & Keith, 2012). To better understand these systems, potential candidate order and control parameters of the system that best describe the outcome of the coordination between athletes are examined. In team sports, dynamics of on-court performance can be described in stable states followed by destabilizations provoked by the attacking team in order to outplay the defenders. When a control parameter reaches a specific critical value, a system becomes unstable and adopts a new macroscopic state (Haken, 2007). In other words, a control parameter can be related to a change in a state of a dynamic (coordinative) system. Passos et al. (2008) revealed that in one-on-one situations common to rugby union, interpersonal velocity and distance (i.e., the difference between each agent) may be such control parameters describing how the system evolves over time. The system in this scenario is a defender trying to tackle an offensive player. In a stable state the defender is preventing the attacker to pass. The attacker aims to destabilize the system by
breaking the defence. The results from Passos et al. (2008) revealed that at the critical interpersonal distance of 4 m, the interpersonal velocity was to be maintained above \(1 \text{ m} \cdot \text{s}^{-1}\) in order to successfully pass the defender. With an interpersonal velocity below \(1 \text{ m} \cdot \text{s}^{-1}\) the defender seemed to be able to tackle the offensive player, albeit not always successfully. Both of these variables are nested in the environment-actor system. In a later study, Passos et al. (2009) used a collective variable – the angle of the defender-attacker vector – to describe performance outcome in rugby attacker-defender interactions. Struggling to clearly identify any critical values, they highlighted how the behaviour emerged from the interaction between the attacker and the defender, emphasizing the presence of indeterminacy in multi-agent systems.

Bourbousson et al. (2010a, 2010b) used dynamical systems principles to study interpersonal coordination in basketball. Bourbousson and colleagues described pattern forming dynamics in basketball based on the individuals’ and teams’ relative position both in one-versus-one and five-versus-five basketball situations. Additionally, a measure describing how team members were spread around the team’s centroid position (i.e., the average positions of all players in a team on the playing field) contributed to understanding the pattern forming dynamics. Relatedly, Frencken, Lemmink, Delleman, and Visscher (2011) searched for a collective variable that captured the dynamics of football. They found that the centroid positions of both teams were attracted towards a strong in-phase relationship in the forward-backward direction, not coincidentally along the axis between both goals. In a follow-up study, Frencken, de Poel, Visscher, and Lemmink (2012) showed that goal-scoring opportunities in football tend to be preceded by more variable inter-team distance. Inter-team distance can thus be considered a collective variable that can describe pertinent processes in this dynamical system that allow for predictions of the system’s outcome. These studies show that these environment-actor variables as described using a dynamical systems approach contain valuable information for human movement science.

### 1.2.3 Ecological dynamics

A recent theoretical development in movement science has seen the fields of ecological psychology and dynamical systems combined in order to adequately address control of human movement in complex and dynamic settings (Seifert, Button, & Davids, 2013). It is
paramount to consider coordination both as an in situ process and a combination of many interacting subcomponents. Davids et al. (2002) have suggested that ‘ecological dynamics’ can aptly inform the pursuit of understanding human motion, or more specifically interactability. Ecological dynamics uses the tools from dynamical systems theory to address issues from ecological psychology. Especially for decision-making in sports, ecological dynamics have been proven a useful tool to come to new insights (Araújo, Davids, et al., 2006). More recently it has been used to describe expert movement systems (Seifert et al., 2013), analyse performance in team sports (Vilar, Araújo, Davids, & Button, 2012) and inform movement education (Brymer & Davids, 2013).

### 1.3 Information for action

In the following section the literature regarding perception for action is more closely examined. The following section also addresses a number of topics that typically fall outside the framework of ecological dynamics. Ecological dynamics provide an excellent tool for many of the phenomena important for this thesis. However, some insights learnt from more cognitive approaches to motor control may indeed help the overall understanding of human movement. First, studies on perception of movement will be discussed after which this section will continue to apply the concepts of perception-action coupling more specifically to distance perception and distance keeping.

#### 1.3.1 Movement perception

##### 1.3.1.1 Biological motion perception

Humans are generally remarkably good at perceiving others’ motion (e.g., Jacobs & Shiffrar, 2005). Anecdotally, this can be observed in how people can typically navigate busy environments such as road intersections without collisions. Without the ability to effectively perceive the motion of others, disorder (and potentially collisions) would be inevitable. More formally, the ability to perceive biological motion has been examined extensively using what Gunnar Johansson (1973, 1976) coined point-light displays (PLD). In the PLD approach, only the point-lights affixed to important body parts (i.e., joints) are visible, omitting all structural environmental and body-specific information. That is, there is no structural information available, leaving only the relative motion of the point-lights to highlight a common set of
spatial relations. Nevertheless, it has been argued that humans can effectively ‘connect the dots’ and are for example able to recognize types of activity (e.g., Giese & Lappe, 2002), identity (e.g., Loula, Prasad, Harber, & Shiffrar, 2005), gender (e.g., Mather & Murdoch, 1994) and even emotion (e.g., Dittrich, Troscianko, Lea, & Morgan, 1996) based on these local sources of information (Blake & Shiffrar, 2007; Runeson & Frykholm, 1983). Furthermore, relative motion can be used to make anticipatory judgements about intention (Sartori, Becchio, & Castiello, 2011) and movement outcomes (e.g., Abernethy, Gill, Parks, & Packer, 2001; Abernethy & Zawi, 2007; Canal-Bruland & Williams, 2010). However, Ikeda (2005) found that recognisability drastically decreased when the PLDs were shown eccentrically, that is, away from the focus of vision. They interpreted this as the neural resource being only embodied for the central vision, highlighting the degree of specialization of perception of biological motion. Moreover, the recognition accuracy of PLDs may not be perfect. The familiarity with the motion appeared to strongly influence the recognition accuracy. For gender recognition, it was shown that due to anthropomorphic variations the accuracy was estimated at 71% based on a meta-analysis of 15 experiments. In terms of perception for action, this may well be a relevant characteristic of recognition of biological motion. It is clear that the perception of human motion partly constitutes of understanding the relative motion of the segments.

1.3.1.2 Common coding principle

Whilst not situated within the ecological dynamics approach, the common coding approach provides an important insight to how humans can recognize biological motion (van der Wel, Sebanz, & Knoblich, 2012). In order to explain how perception and action are linked, Prinz proposed the framework of the common coding approach² (Prinz, 1997). The common coding approach explains that for effective action (planning) and for effective perception of action (i.e., recognition of biological motion), both concepts share a representation. That is, action and perception are ‘coded’ in the same way to allow for fluent coupling between perception and action (Rizzolatti et al., 1996). Using brain-imaging techniques, B. Calvo-Merino, Glaser, Grezes, Passingham, and Haggard (2005) showed that dancers looking at dance-forms they were trained in have stronger mirror-neuron activity than dancers watching less familiar dance-forms. This activity is mostly found in the premotor cortex, indicating a strong link

² Although the common coding approach has been developed from a cognitive rather than ecological dynamics framework, I deemed it an important addition for this thesis as it provides a structure through which the connectedness between perception and action may be understood.
with actual movements (which also have an active premotor cortex before initiating a movement). In fact, in a follow-up study it was shown that ballet dancers looking at ballet moves specific for their gender have a greater mirror-neuron activity compared to when looking at ballet moves typically executed by the other gender (Beatriz Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006). Although it has not been excluded that visual expertise may also elicit more motor-neuron activity, this follow-up study does emphasize the importance of movement experience of the movements observed. There is indeed convincing evidence that the mirror neuron system plays a large role in the perception-action process (Wiggett, Hudson, Clifford, Tipper, & Downing, 2012). Wiggett et al. (2012) examined how participants perceived different hand-action sequences when either having learnt the sequences either by observation, or by action. When the participants had a ground for common coding, based on having learnt the sequences by action, the visuomotor areas responded most strongly. The studies discussed above have all focused on the recognition of movement; however, the missing link in this body of research is arguably the omission of perception of action while concurrently moving oneself. The main limitation is that current brain-imaging techniques (such as fMRI) do not allow for head movement without loss of imaging resolution.

Alternatively, experiments can be designed to look at the behavioural response. It has also been shown perception is affected when an observer has to act as well. For example, Knoblich and Flach (2001) showed that in a darts throwing task, participants can better predict movement outcome (i.e., the dart’s landing position) of one’s own movements compared to someone else’s movements. Observation of point-light displays is more accurate when the observers are moving in the same way as well (Jacobs & Shiffrar, 2005). Participants were watching point-light displays of a walking person whilst standing still, cycling, or walking. The greatest sensitivity to identifying walking speed was found when the participant was also walking. The authors argued that the potential to coordinate one’s own actions with the observed actor strongly facilitated perception of the other’s actions. These findings highlight that there is an interaction between the process of perceiving and acting (Knoblich & Flach, 2001) as suggested in the common coding theory (Prinz, 1997). Although there are many conceptual differences with the cognitive and ecological psychology, the common coding theory does highlight a structure that may be able to explain the intricate link between perception and action.
1.3.2 Perception-action

The environment-actor relationship is a central topic for two contrasting theories on perception. When studying human movement, the detection of information and the behaviour generated based on this information are crucial for developing an understanding of how goal-directed behaviour can emerge. Traditionally, perception and action have often been studied separately, partly assuming representation-based information-processing or indirect perception (Williams, Davids, & Williams, 1999). As such, perception of visual information was considered subjective and merely indirectly correlated with the objective quality to be perceived, similar to Brunswik’s (1943) concept of distal and proximal stimuli. That is, visual information is meaningless until the information is processed by a central controller (i.e., the brain). This approach is also referred to as the information-processing approach, or representational realism (Runeson, Juslin, & Olsson, 2000). Hossner (2009) argues perception of the environment can be indirect as long as the representation of pertinent properties of the environment has an interpretable link (acquired through motor learning or skill acquisition) with the objective world. Meaningless stimuli are linked to actions of which the effect is only known in terms of a new meaningless stimulus. Within the framework of ecological psychology, however, it is argued that perception is not indirect, but can in fact be described as direct. Instead of having ‘interpretable links’ between perception and action, it is argued that actors’ behaviours emerge as a function of the law-like relationships within the environment-actor system (Turvey, 1990). As such, perceived information is directly accessible for action without mental calculation (Jones, 2003). Furthermore, as has become a central focus within ecological psychology, the perception and action are reciprocally coupled. That is, conceptually differentiating between perception and action as separate processes is redundant, as perception is directly governed by action and vice versa. Gibson (1979) even argued, somewhat radically at the time, that the dichotomy of ‘perception and action’ is non-existent. Instead, processes of perceiving and acting are situated within an environment-agent system (Bootsma et al., 1997), in which perception-action is operationalized as one inseparable unit. In Gibson’s guide to discovery for perception of visual information (Gibson, 1979), he proposes the optical flow as a rich source of perceptual information for action. Optical flow refers to the light pattern that can be observed through the relative motion between observer (i.e., actor) and environment. Gibson explains the idea came from one of the many train journeys he made, during which he would be standing at the back of the train observing how visual information raced past and disappeared in the distance. This
flow of information is important for many tasks, and interestingly can be induced or mediated by both the environment and the actor. It is therefore a great example of information for action that is available within the environment-actor system. The coupling between subsystems is guided by some form of information transfer. Although in specific cases subsystems (i.e., agents) are physically coupled (de Brouwer, de Poel, & Hofmijster, 2013; Harrison & Richardson, 2009), in most dynamic situations (inter-agent) coupling is mediated through (predominantly visual) perceptual information (e.g., Meerhoff & De Poel, 2014). From the perspective of ecological dynamics, the perception and action have to be considered as overlapping, or even inseparable (e.g., Araújo et al., 2005; R. C. Schmidt & O'Brien, 1997; Seifert et al., 2013).

### 1.3.2.1 Affordances

An actor that can directly perceive the environment it is immersed in is proposed to perceive this environment in terms of what it affords to the actor. Perception is the detection of or attunement to functional units referred to as ‘affordances’. In short, Gibson described affordances as what the environment offers, provides or furnishes to the actor in terms of its action opportunities. An affordance is a characteristic of the environment-actor system that expresses the opportunity for action, which depends on both the actor and its environment. A typical example of an affordance is the extent to which stairs are climbable, which is related to riser height and leg length (Warren, 1984). Biomechanically, the maximal and most energy-efficient riser height can be determined objectively. Based on their leg-length in relation to the riser-height, participants could accurately predict these body-scaled or environment-actor qualities. In another example, Franchak, Celano, and Adolph (2012) showed that perceiving the opening of a doorway as ‘passable’ not only depends on body-scaled variables such as height and shoulder width, but also takes into account that the body can change shape in order to pass through openings. In other words, the dynamic properties of walking are important in addition to any body-scaled variables. Thus, the extent to which the environment affords an actor to interact depends on both the actor and its environment. For some philosophers, this description is somewhat problematic, as the term ‘affordance’ itself is hard to define. The most radical aspect is that it negates the existence of a central controller, whereas traditionally the brain has always been considered the central controller. Rather than having to compute information to generate action, affordances allow for direct attunement with the environment. Gibson (1979) implied that cognition is in fact embodied. In that
context the meaningful properties of the environment-actor system make up what falls under ‘information’. As such, rather than perceiving information, an actor detects information that is meaningful to its actor-environment relationship. Cognitive processes are not restricted to the mind in isolation, but can only be understood as inter-connected with the body and environment. Referring to the example of climbing stairs, the cognition to perceive a riser as climbable does not reside (solely) in the brain, instead it exists as an embodiment of the leg length and the riser height. Chemero later argued that embodied cognition should be at the core of explaining ‘representation-less’ and ‘computation-less’ coupling between perception and action (Chemero, 2003). To explain perception and action, affordances provide an excellent concept to incorporate the ideas of ecological psychology.

1.3.2.2 Naturalistic perception

There are some essential constraints to the human sensory systems for perceiving the outside world (e.g., sensitivity to certain bandwidths of light and sound frequencies), but nevertheless there are ways to detect relevant patterns in the environment for action regulation. If perception is indeed based on a functional relationship between actor and environment as mentioned above, it may imply detection of information pertinent for the action intended (i.e., specifying information). For example, when catching a ball, specifying information would inform about when (and where) to close your hand around the ball. However, Raab, de Oliveira, and Heinen (2009) explained how in the theory of direct perception, a shift could be made from specifying to non-specifying information. Non-specifying information in this context refers to information that is not necessarily related to the action intended. It can be correlated with the action intended, but it does not necessarily specify it. For example, the upper trunk yaw and out-foot placement can be used to judge a person’s running direction, but these do not necessarily correlate as a person can deceive an observer to be headed in one direction whilst in fact heading to another (Brault, Bideau, Kulpa, & Craig, 2012). Initially, the use of non-specifying information seems somewhat contradictory – after all, how can perception be direct if that what is perceived is not true? Raab et al. (2009) use bounded rationality to explain the use of non-specifying variables. Bounded rationality emphasizes that a decision-making process is limited by knowledge, time and cognitive capacity. Instead, rationality is based on cues or shortcuts that can indeed be processed. In that light, motor learning is considered as the familiarization with the reliability of (non-)specifying sources of information (or cues). Interestingly, the visual system has not necessarily evolved to pick up
specifying information or to be accurate, but it developed in the first place to be effective or functional (Withagen & Chemero, 2009). Essentially, natural selection has pushed the visual system to develop ‘good enough’ pattern recognition for survival (Nilsson, 2009). Particularly with respect to the objective-subjective discussion, defining the objective-subjective might be redundant for perception-action. It is in principle not necessary to pick up all information, or even to pick up accurate information. Thus, an important addition to Gibson’s theory on perception is that from an evolutionary perspective, selection can lead to suboptimalities (i.e., becoming reliant on non-specifying information), as long as the information is specifying enough for the purpose of the task (Chemero, 2003; Withagen & Chemero, 2009).

1.3.3 Distance perception

1.3.3.1 Global motion information

One way to pick up distance-related information from the environment is by globally picking up how objects move in relation to each other. In the context of this thesis, global information is obtained across multiple locations or holistic, in contrast with local information which is obtained from specific locations (cf., Huys et al., 2009). For example, dynamic occlusion (an object is partially blocked because it is behind another object) and motion parallax (farther objects move less across the field of view of an observer) may provide information of the relative distance of two (or more) objects. Based on the head position of an observer, Ono, Rogers, Ohmi, and Ono (1988) provided participants with contrasting information of both dynamic occlusion and motion parallax. Rather innovatively they used an electromagnetic head tracker to create the motion parallax on a 2D monitor showing two layers of a dotted display. As a participant moved his/her head, the second – and thus virtually farthest – layer of dots would move at a slower rate than the first layer of dots, hence creating the illusion of depth perception. By manipulating the gain (i.e., the different speeds of the layers of dots) they could manipulate the relative depth. They showed that participants rely on motion parallax when objects are relatively close to each other, whereas participants rely on dynamic occlusion when objects are far away from each other. Both strategies thus provide useful information, depending on how the environment is furnished. However, these sources of information are limited in providing functional information on the distance of these objects in relation to the observer (i.e., how far the object is from the observer).
One optical variable that does inform about distance in relation to the observer is an object’s optical size. An object that is expanding is approaching towards, and an object that is shrinking is receding from the observer. This change in optical size can also be referred to as the object’s expansion-compression. Recently, Yoonessi and Baker (2013) used a similar setup as Ono et al. to examine depth perception via expansion-compression and compared it with motion parallax. They manipulated expansion-compression based on the head movements. When covering the same distance, objects that are closer undergo a quicker change in optical size than objects further away. When the motion-parallax cues contradicted expansion-compression cues, it was found that expansion-compression was most relied upon compared to motion-parallax at a broader range of depths (between 1 and 64 cm). This supports that many cues can inform an observer about distance, but the specific setting dictates the usefulness of each source of information.

1.3.3.2 Grasping Tau

In line with ecological dynamics, an attempt was made to identify a universal optical variable that specifies distance in relation to an observer, or more specifically, a variable that regulates timing skill. That is, a specifying source of information was sought after that could directly mediate interceptive action. A candidate optical variable was introduced by Lee (1976). He noted that the change in optical size of an object (i.e., rate of change in visual angle) has a direct relationship with time to contact. More specifically, it was argued that the relationship between the visual angle ($\alpha$) and the rate of change of that visual angle ($\dot{\alpha}$) can directly specify time to contact ($\tau = \frac{\alpha(t)}{\dot{\alpha}(t)}$). Initially inspired for keeping distance in traffic, Tau ($\tau$) was suggested to explain how plummeting gannets visually timed the instant of closing their wings when hunting for fish (D. N. Lee & Reddish, 1981).

Methodologically, an insightful way of capturing how coordination dynamics are affected by (non-) specifying information is to manipulate the optical variable that is thought to contain relevant information. One of the more striking attempts to grasp the role of Tau in guiding human coordination is the Savelsbergh et al. (1991) study on regulating hand-aperture for catching different sized balls. They manipulated Tau by letting their participants catch an approaching ball that started as the same size as the large ball, but during its flight it deflated until it was the same size as the small ball. Therefore, Tau information was non-specifying for time to contact, as the change in optical size did not correspond naturally with its distance.

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relative to the catcher. Furthermore, this was done in a dark room with a lit up ball, so no information about the context could be picked up for estimating time to contact. Interestingly, it was found that using the only available source of information, Tau, participants could successfully guide their hand-aperture to catch the manipulated balls. Moreover, it was found that the hand-aperture was changed similar as for the large ball in the beginning of the deflating ball trajectory, but the hand-aperture smoothly changed to a smaller hand-aperture as the ball approached the hand. The authors surmised that hand aperture was indeed directly specified by Tau. However, it is argued that the Tau-hypothesis is not necessarily universal for any timing skill. Tresilian (1999) puts forward four pertinent caveats: Tau is not sensitive to acceleration; Tau only provides timing information in relation to the eye (and not, for example, an extended hand with which to catch a ball); Tau only applies for spherically symmetric objects; and Tau is only accessible if the changes in visual angle exceed the sensitivity threshold (i.e., Tau cannot be observed for small objects, or objects that undergo small changes (see also Andersen & Sauer, 2007). Nevertheless, distance-related information can clearly be picked up by some form of global information. Depending on the specific setting, one type of information may be preferred over another. Furthermore, global information can also inform about the environment-actor system, albeit with some restriction.

1.3.3.3 Lateral distance perception

Movement coordination typically crosses multiple planes. The above visual angle related variables mostly apply to movements to and from an observer. In other movement scenarios distance needs to be perceived in the lateral plane. For example when intercepting a moving target a simple model that may explain the coordinative strategy is maintaining a constant bearing angle (Chardenon, Montagne, Buekers, & Laurent, 2002; Chardenon, Montagne, Laurent, & Bootsma, 2004). The visual information that specifies imminent perception is still related to the visual angle, but given its change in movement direction it is attuned to differently compared to visual angle information for distance keeping in the same movement plane. In a study on collision avoidance between two walkers Olivier, Marin, Crétual, and Pettre (2012) described how interpersonal coordination was governed by the minimum predicted distance (MPD). Based on critical values of MPD movement strategies could be predicted: either the actors have to adjust to avoid collision, or the actors can continue without adjustment. In a follow-up study Olivier, Marin, Crétual, Berthoz, and Pettre (2013) revealed an asymmetry in the coupling between the agents (cf., Meerhoff & De Poel, 2014) as the actor
that had to give way to the other contributed more to the coupling than the other actor. Another setting in which lateral distance perception has been closely studied is catching objects approach an actor, but require the actor to move laterally in order to achieve interception. For example when catching a ball passes an actor about an arm’s length to the side requires the actor to estimate the lateral distance in order to timely catch the ball. McBeath, Shaffer, and Kaiser (1995) put forward that baseball outfielders may use a linear optical trajectory (LOT) in order to determine where to run to catch fly balls. This strategy is based on maintaining a balance between vertical and lateral optical angular change, and can be adopted without knowing the distance to the ball or the home plate. In this thesis, an emphasis is put on the perception of distance in order to maintain a distance (see Section 1.3.4). Strategies that are based on perceiving distance in order to intercept therefore do not directly translate keeping distance. In most cases however, keeping distance can be considered a special case of distance perception where the moment of interception is undefined.

1.3.3.4 Effort-based distance perception

Distance as a real-world measure, however, is perhaps not the same as the perceived distance (see Section 1.3.2.2). This has led to some interesting approaches on distance perception where the coupling between perception and action becomes clearly apparent (Adolph, Joh, & Eppler, 2010; Proffitt, Stefanucci, Banton, & Epstein, 2003; Stefanucci, Proffitt, Banton, & Epstein, 2005; Witt, 2004; Witt & Proffitt, 2008). Proffitt et al. (2003) showed that the perceived distance is related to our intentions and the effort associated with that intention. Participants had to throw different balls with different weights to a target and estimate the thrown distance. Heavier balls were estimated to have been thrown further, as it was perceived that more effort had been put into it. In a second study, the same relation between the anticipated effort of intended action and perceived distance was found for estimating distances on hills. The gradient of the hill, and its corresponding perceived effort to climb it, made a distance appear farther. This is a clear example of how the perception of the environment is strongly guided by its action possibilities, however, it has to be noted that the repeatability of the studies on effort-based perception has been contested (Firestone, 2013; Woods, Philbeck, & Danoff, 2009).

Evidently, distance perception is not always veridical and can be strongly affected by the circumstances. It is, however, crucial to realize these findings do not necessarily indicate a
malfunctioning visual system; in fact, it falls in line with the proposition of naturalistic perception (Withagen & Chemero, 2009). The perception of the environment does not have to be veridical or accurate, as long the functional relationship between the environment and the agent can be perceived. As such, action planning does not require an optimal visual system, instead, actors only need to perceive the environment in relation to the intended action. To link this back to the effort-based perception (Proffitt et al., 2003): an objective perception of distance is redundant; instead the perceived distance is influenced by the effort it takes to cover the distance.

1.3.4 Distance keeping

The distance between an agent and something in its environment is important in many situations. For example, keeping distance is a key (survival) mechanism of vertebrates (Couzin & Krause, 2003) and in traffic (J. Lee & Jones, 1967), but also in sports (Passos et al., 2011). Couzin and Krause (2003) describe how vertebrates exhibit collective behaviour without a clear leader or pre-established pattern. Instead they use self-organization to explain how each individual agent (a wildebeest in a herd, a fish in a school or a bird in a flock) can adhere to simple rules without knowing the group outcome. These simple rules are based on inter-agent distance, making it a key survival characteristic. When driving a vehicle through traffic, keeping distance is important because it is essential to avoid accidents. And even in sports, the distance between agents can provide useful insights: Passos et al. (2008) found that within a combination of a specific interpersonal distance with a specific value of the first derivative of distance, relative velocity predicted the outcome in one-versus-one sub-phases of rugby.

1.3.4.1 Crowd navigation

An illustrative daily life example where keeping distance plays an important role is navigating in crowds. For example, when trying to catch a train on a busy train station, one has to navigate as fast as possible through a crowd, preferably without collision. Not only does this person have to find his way through the crowd, this person must also take into account that the crowd is constantly changing. In other words, the change over time of the crowd has to be directly incorporated in this individual’s behaviour if he wants to be on time for the train. This evidently requires a strong coupling between perception and action. Additionally, when this person is running through the crowd he is affecting the behaviour of the crowd. Hence, the
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relationship between actor and environment is bi-directional (Olivier, Bruneau, Cirio, & Pettré, 2014). One possibility upon seeing someone trying to catch his train could be that a member of the crowd steps aside, which accordingly changes the optimal route. Gérin-Lajoie et al. (2007) observed that expert athletes are better at navigating through crowds, indicating superiority in navigational skills in complex obstructed environments. The authors suggested that experts appear to be able to use a mix of strategies involving both explicit planning of a path and attuning to online (i.e., real-time) visual information. In a dynamic situation, actors are hypothesized to attune to a specifying variable such as the visual angle (Rio, Rhea, & Warren, 2014). It can be argued that by merely maintaining either of these suggested parameters within a certain range, complex behaviour can emerge. For example, using computer modelling based on global behavioural variables, in this case defined by an observed clear path, Moussaïd et al. (2011) reliably showed that complex crowd behaviour can emerge through the self-organized interactions between the individuals who are part of the crowd.

1.3.4.2 Follow the leader

Previously, the potentially universal specifying variable for distance-related coordination, Tau was discussed (see Section 1.3.3.2). However, the regulation of the distance using Tau is only possible in action where a collision or interception is imminent. This makes its direct application to interpersonal coordination questionable. Recently, Rio et al. (2014) have tested a number of visual control strategies for maintaining distance in pedestrian following. Their first study tested which strategy fitted best by manipulating the starting distance which a follower was required to maintain from a leader. After moving at a constant velocity for a varied amount of time, the leader changed velocity. The models that used simple speed and distance based component (derived from the visual angle, $\alpha$) were found to best predict the follower’s corrective behaviour to keep distance as the leader accelerated. In their second study the researchers tried to extrapolate where the information for such distance and speed regulation might be observed from. Two prevailing theories for visual perception were tested. First, binocular disparity allows for depth perception that can inform about distance up to several meters (Cutting & Vishton, 1995). Secondly, the optical size – or visual angle – can inform about distance (Andersen & Sauer, 2007; Kunnapas, 1968; Levin & Haber, 1993). Using a head-mounted display, participants followed a virtual leader in the form of a pole. Again, after moving at a constant velocity for a varied amount of time, the velocity of the pole
was changed. Using virtual reality, the display of the pole was manipulated to either show a change in speed specified by a change in binocular disparity, by visual angle, or finally by a combination of the both. Based on the follower’s response, it was found that regardless of the congruence, disparity-specified acceleration had a minimal effect. Expansion-specified acceleration, on the other hand, had a strong effect on the change in the follower’s speed. This study thus confirms the pertinence of the change of visual angle when keeping distance as a follower.

A study performed by Ducourant, Vieilledent, Kerlirzin, and Berthoz (2005) revolved around how interpersonal distance regulates interpersonal coordination. The authors noted that in fencing, each fencer has their own preferential distance for both offensive and defensive displacements. Interestingly, they also noted that these distances can be modulated by the opponent’s behaviour; that is, the relationship is bidirectional. In this light, Ducourant et al. (2005) aimed to investigate how an individual adjusts its locomotion according to another person’s locomotion in a follower-leader task. They looked at coupling on segmental levels and on global levels. They showed that individuals used a reactive and secure strategy, coupled onto a global level. This was evident through the lack of similarity on a purely segmental level: followers took fewer steps, covered less distance and moved slower. Ducourant et al. (2005) concluded that the central nervous system of the followers did not regulate locomotion on the basis of a (slightly delayed) copy of the leaders’ actions, but that both individuals were involved in a bidirectional interaction. It was hypothesized that the follower wasn’t so much copying the leader’s behaviour as he or she was synchronizing to the intentions of the leader.

1.3.4.3 Social context

Interestingly, humans regulate behaviour based not only on visual information that specifies distance, but also on social interactions (Oullier, de Guzman, Jantzen, Lagarde, & Kelso, 2008; R. C. Schmidt & Richardson, 2008). For example, the social context may strongly influence how interactions take place. R. C. Schmidt, Christianson, Carello, and Baron (1994) showed in an experiment that characteristics of an individual’s personality can be picked up through observation of that individual’s coordination patterns. In fact, these traits may limit the extent of social interaction. R. C. Schmidt et al. (1994) used the Social Skills inventory (Riggio, 1986) to determine an individual’s social competence (high or low) and consequently ordered pairs of individuals in heterogeneous (high-low) and homogeneous (high-high and
low-low) pairs. It was shown that social coordination was facilitated if there was reciprocity (leader-follower) rather than symmetry (leader-leader or follower-follower). In other words, coordination between individuals seems to depend at least partly on the social competence dynamics that exist between the individuals. Apart from social competence, other social constructs can also play a role. For example, how familiar two individuals are with each other, or possibly even how much they like each other (R. C. Schmidt et al., 1994).

It is important to realize that there are many ways an agent can obtain information about another agent’s intentions. Depending on the task, other global information sources as task and environmental constraints (e.g., the out of bounds rule in sports) may (partially) inform about an agent’s position and (intended) movements. Some studies suggest that personal space, cultural customs and taboos influence behaviour in social coordination (Hayduk, 1983). People tend to maintain a radius of personal space (of about 50 cm) that is not invaded during normal social interaction (Ashton, Shaw, & Worsham, 1980; Hayduk, 1983). More recently, this effect has been repeated in virtual environments also (Bailenson, Blascovich, Beall, & Loomis, 2001; Bailenson, Blascovich, Beall, & Loomis, 2003). Although it has to be acknowledged that social interactions undoubtedly play a role in how humans coordinate their movements together, for the purpose of this thesis this was deemed beyond the scope.

1.4 Skilful interacting

Interpersonal coordination research has recently attracted increased interest as a way to describe and understand how agents interact in order to deliver coordinated team performances (Balague, Torrents, Hristovski, Davids, & Araújo, 2013; Duarte et al., 2013; Duarte et al., 2012; Frencken et al., 2012; Passos et al., 2011; Vilar, Araújo, Davids, & Button, 2012). Given the framework of ecological dynamics, coordinated behaviour extends beyond the movements of an individual by itself and incorporates everything from the environment that influences the movement outcome. For example, a successful free-kick in football requires accurately timed coordination of the trunk, the legs, the foot and lastly the environment. In this case the important characteristics of the environment are the distance to the target, wind conditions and the positioning of the goal-keeper (and other players). Coordination is thus achieved by also controlling all of these – and more – components of which the environment consists. A skilled individual can incorporate each of these components in their actions. As suggested above (see Section 1.1), the skill of interacting can
be surmised as the interact-ability. Most notably, interacting with others specifically (whether cooperating or competing) may constitute skilful coordination: as the level of competition increases, the skill level of the person being interacted with also increases, thereby making successful coordination even more difficult. Fundamentally, interact-ability is comprised largely of interpersonal coordination. For an observer, “skilled athletes never seem to merely react to unexpected events, but appear to operate in the future,” as argued by Williams et al. (1999, p17). Furthermore, the importance of interact-ability for interactive team sports has indirectly been described by Eccles and Tenenbaum (2004) who aptly state that an expert team is more than a team of experts. That is, the ultimate skill in invasion sports is the ability to translate the individuals’ skills into the excellence of the team performance.

1.4.1 Perceptual-motor expertise

As outlined in the sections above, coordination emerges through the coupling of perception and action. An expert’s superiority may be partially comprised of superior motor skills (e.g., strength, agility), but it has also been shown that experts have superior perception skills (Connors, Burns, & Campitelli, 2011; Gegenfurtner, Lehtinen, & Saljo, 2011; Sebanz & Shiffrar, 2009; Travassos et al., 2013; Williams, Ford, Eccles, & Ward, 2011). Chase and Simon (1973) proposed that experts have superior pattern recognition skills. They tested how accurately chess players could memorize chess game situations. In one set of conditions, participants were presented with realistic chess scenarios, whereas in the other set of conditions, participants were presented with random – unrealistic – chess scenarios. Experts were superior in memorizing the former set of conditions, but not the latter. This indicates that experts use the meaningful relationships between the chess pieces in order to accurately size up the situation. This skill may apply to more dynamic situations, like invasion sports. Experts would have the visual tools to effectively obtain pertinent information from the environment. This has in particular been shown in the anticipation skill using temporal occlusion paradigms. Participants would be presented with a display of coordination, which would then be abruptly occluded, after which participants would be asked about the sequence of actions following the occlusion. Repeatedly, experts were shown to be more accurate than novices in anticipating the subsequent movements (Abernethy et al., 2001; Abernethy, Zawi, & Jackson, 2008; Le Runigo, Benguigui, & Bardy, 2005; Sparrow & Sherman, 2001). Furthermore, it has been suggested that the effect of expertise on anticipation skill is specifically linked to motor experience (Canal-Bruland & Schmidt, 2008). That is, referees –
who are arguably perceptual experts – do not have the same anticipation skills as experts with motor experience.

1.4.2 Deceptive movement

An interesting component of invasion sports is that interpersonal coordination is not only based on cooperation, but also on competition. This means that an individual’s skill at picking up specifying information should also take into account that opponents may indeed use deceptive movements to misguide a defender. Sebanz and Shiffrar (2009) asked experts and novices to determine whether a basketball player was faking a pass, or actually going to pass. Experts predicted fake passes more accurate than novices, but only when the passes were shown as a video; novices and experts performed equally when only presented with static images. It is thus argued that an expert’s interact-ability includes its susceptibility to deceptive movements (Jackson, Warren, & Abernethy, 2006). For the complete skill set, experts should always be able to effectively influence others, as emergent role-taking may be crucial for effective interpersonal coordination (Meerhoff & De Poel, 2014).

1.4.3 Outline of the thesis

An argument has been made for the implications of ecological psychology and its representative design, the different approaches to perception, and the dynamical character of coordination in interpersonal coordination. The individual’s ability to coordinate in such a dynamical setting must attain a combination of skills, as evident in their accurate and efficient coupling of information and action. Inspired by the study on grasping Tau by Savelsbergh et al. (1991) (see Section 1.3.3.2), the current thesis adopted a manipulation of visual information to regulate action. The task consisted of following a leader (based on Ducourant et al., 2005), that is, the follower had to keep distance with the leader. Keeping distance is a fundamental coordination which is a part of, for example, one-versus-one defence (e.g., Passos et al., 2008). Ducourant et al. (2005) have shown that followers synchronize with a ‘global’ variable, for example relative position, rather than mimicking a ‘local’ variable, such as step frequency or step size. Combining the two studies, the nature of information necessary to couple one’s behaviour to another in a representative yet controllable task was considered.

Instead of having two persons interact with each other, a model participant was pre-recorded and displayed on a life-size projection screen. This allowed for the manipulation of visual
information of a leader. This manipulation allowed for direct comparison between trials, improving experimental control by eliminating potentially bidirectional interactions that could occur between a live leader and a live follower (Meerhoff & De Poel, 2014). In all studies, a virtual reality setting was used in which a leader was video-displayed on a large screen. The focus of the first study was to examine the specificity of visual angle information to follow a leader. Participants followed a pre-recorded leader that was either presented as a fully animated avatar, or as a back-and-forward moving sphere. As a sphere does not have any moving segments (i.e., limbs), displacement is only specified by visual angle information. The participants’ movement responses were recorded to examine the effect of this manipulation of available information.

In the second study, it was further explored whether information for action could sit on a spectrum from local to global motion. A distinction was made between segmental motion, cadence and expansion-compression information. Similar to study one, the participants’ movement responses were examined to understand the role of each type of information. Additionally, some key task constraints (e.g., leader regularity, viewpoint) were manipulated to examine how these constraints influenced the perception-action coupling.

In the third and last experiment, the generality of the dynamics of back-and-forwards following (as tested in study one and two) was tested for following a leader from side-to-side. Movements often take place along multiple axes, therefore it was important to expand the understanding of distance regulation to lateral movements. Furthermore, lateral following allowed followers to maintain a physical distance rather than a virtual distance.

This thesis aims to contribute to the understanding of motor control in interpersonal coordination and build towards an understanding of what processes may constitute (skilful) interacting, and further the understanding of interact-ability.
Chapter 2

Regulating Distance

Distance Regulation when Following the Leader:
Contrasting the Availability of Global and Local Motion Information
2.1 Introduction

Many motor skills require continuous coordination with the environment. Interestingly, complex behavioural dynamics emerge from very simple low-level interactions with other agents (e.g., Hildenbrandt et al., 2010). In order to understand how humans coordinate their actions effectively, it is pertinent to understand what types of information are available and used in regulating behaviour. Gibson (1979) proposed optical flow as a rich source of perceptual information which can specify pertinent properties of the environment-actor system (Bootsma et al., 1997). One of the fundamental coordinative tasks occurring in many daily situations is keeping distance to (moving) objects or other agents in our environment. Optical flow may indeed guide agents when keeping distance. More specifically, optical expansion (indexed by e.g. the change in visual angle, see 2.1.2), an important feature of this flow, has been proposed to be a key physical quantity for many distance regulation tasks (e.g., plummeting gannets, tailgating, or catching balls; Chapman, 1968; D. N. Lee, 1976; D. N. Lee & Reddish, 1981). This study uses a follow-the-leader task to examine the perception-action coupling and thereby increase understanding of distance regulation in human locomotion. Specifically, this study will explore whether expansion and its inverse, retraction, information may be sufficient information in such distance regulation.

Perception and action are coupled in a way that one leads to the other equally so as vice versa (Schöner et al., 1998) and therefore have to be operationalized as one inseparable unit. This idea is rooted in the concept of representative design (Brunswik, 1956) and has been experimentally confirmed by for example Dicks and colleagues (Dicks et al., 2009). Furthermore, when examining inter-agent coordination, the perception-action coupling is potentially reciprocal between all agents involved (Knoblich & Sebanz, 2008). For follow-the-leader coordination this means that even when roles may be clearly defined, in addition to the leader influencing the follower the follower also still influences the leader’s movements (Ducourant et al., 2005). This is even the case when the leader is not able to see the follower (Meerhoff & De Poel, 2014). The current study therefore looked at the (whole-body) movement response of followers maintaining (virtual) distance with a back-and-forth moving pre-recorded video-displayed leader. As such, there was no coupling influence possible from the follower to the leader.
2.1.1 Follow-the-leader

Regulating distance is part of many types of behaviour: in social context (Perry, Rubinsten, Peled, & Shamay-Tsoory, 2013), during transport where distance is regulated to avoid collision (Olivier et al., 2013), or in sports to intercept or avoid opponents (Passos et al., 2008). Arguably, every one-versus-one (sub-) phase of for example basketball, boxing, rugby, kendo or fencing relies on effectively regulating inter-agent distance (Bourbousson et al., 2010a; Ducourant et al., 2005; Hristovski, Davids, Araujo, & Button, 2006; Okumura et al., 2012; Passos et al., 2008). Inspired by the dyadic interactions during fencing, Ducourant et al. (2005) used a follow-the-leader task to examine the effect of inter-agent distance on dyadic locomotor coordination. This task provides an excellent tool for studying inter-agent distance. Whilst facing each other, the assigned follower was instructed to maintain constant distance to the assigned leader, who was instructed to freely walk back and forth. Although they found that the followers’ step characteristics (e.g., length, velocity, frequency) were different from the leaders’ step characteristics, the followers were able to stably maintain the initial inter-agent distance. The authors therefore surmised that, rather than the follower responding to more ‘local’ level information (e.g., the leader’s steps), the inter-agent coupling took place on a more ‘global’ level. Local information may be derived from the body segments (e.g., limbs) in relation to each other, whereas global information refers to the perceived object as a whole in relation to the environment and, of course, these two categories of information sources are not necessarily mutually exclusive. This work gives rise to the question what information exactly governs such inter-agent locomotor coordination. Information for action to regulate distance in a follow-the-leader study has been examined by Rio et al. (2014). In their task, followers had to maintain distance with a confederate leader that changed velocity whilst walking in forward direction. Subsequently, the followers’ behaviour was compared to a range of behavioural models to test which would match closest. They showed that followers most likely adopt a simple speed-matching model. However, it was beyond the scope of their study to examine what information followers specifically attuned to. Therefore, the current study further explores the hypothesis that follow-the-leader coupling can be regulated by global information alone in the absence of local information.
2.1.2 Global motion information

The ‘global’ level variable Ducourant et al. (2005) alluded to, might be related to the follower’s perception of expansion-compression movements of the leader, expressed by the optical expansion rate (Durgin & Li, 2011; Ito & Matsunaga, 1990; Regan & Gray, 2000). In this setting, visual angle expresses the angle between the straight lines from the extremities of the object to the point of observation (as illustrated in Figure 2.2 and Figure 2.6). It is inversely proportional to distance in relation to the observer: the smaller the distance to an object, the bigger the optical size and, hence, the angle. As such, visual angle \( \alpha \) directly specifies the distance to an object, with the proviso that the physical object size stays (close to) constant. Previous research has shown that the visual angle is a useful source of information for the perception of distance (e.g., Rio et al., 2014). Indeed many studies have shown how changes in visual angle are pertinent for a number of discrete tasks: interception, collision avoidance and distance keeping in general (Fajen & Warren, 2007; Regan & Gray; Rio et al., 2014; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). Functionally, if a distance was to be kept constant the rate of change of \( \alpha \) should be nulled. The current study extends the relationship of visual angle in discrete tasks to a continuous follow-the-leader task. Furthermore, most studies focus on the use of \( \alpha \) in interceptive tasks, where distance always decreases. When the distance increases, \( \alpha \) might be used differently. Firstly, the relationship between visual angle and distance is not linear, as visual angle and distance are not proportional by law. As such, for a given change in distance, a decrease in distance leads to a larger change in visual angle than an increase in distance. In a back- and forth follow-the-leader task, this asymmetrical characteristic of visual angle might in fact affect the follower’s behaviour. It is therefore hypothesized that the movement direction of the leader in relation to the follower (i.e., either approaching or receding) influences the follower’s behaviour differently. Because for the follower, the visual angle is increasing faster in relation to the distance covered when the leader is approaching than when the leader is receding, implying that approaching movements contain clearer information for changes in distance, approaching movements of the leader are hypothesized to be more accurately followed than when the leader is moving away from the follower.

\(^3\) Although according to some definitions the rate of optical expansion can also be referred to as a local change in the optic flow, for this thesis optical expansion is referred to as a global variable as it describes the pickup of holistic information across multiple locations (Canal-Bruland, van Ginneken, van der Meer, & Williams, 2011; Huys et al., 2009).
2.1.3 Local motion information

Converse to the hypothesis in the previous paragraph, it can also be stated that more ‘local’ sources of visual information may be more useful for inter-agent coordination. Posture or limb movements (i.e., segmental motion) might inform about intended actions (e.g., Diaz et al., 2012). Local motion information refers to how the body parts (e.g., limbs) of the observed agent move in relation to each other (cf., local or relative motion information, cf., Roca, Ford, McRobert, & Williams, 2011) and can for instance inform in detail about many step characteristics (e.g., step length, duration, velocity). Although local motion information is rarely studied in isolation (see for an exception Beintema & Lappe, 2002), the most effective way to accentuate local motion information is using a point-light display (Johansson, 1973). Note that there still is some global motion information available through the relative size of the point-lights as a whole, but the dominant information available is limited to the limbs in relation to each other. Studies have shown that humans do exploit these perceived local kinematics. In addition to responding to displacement to regulate distance with an object/agent, many tasks also require anticipating discrete changes in coordination. An example of such a critical event can be a change of direction by an attacker in an attempt to pass the defender in a sub-phase of rugby (Passos et al., 2008).

Local motion information has been found to be pertinent for detecting anticipatory cues. For instance, Abernethy et al. (2001) showed that skill level is related to anticipation success of squash services when presented with point-light displays (i.e., predominantly local information). Also in badminton, Abernethy and Zawi (2007) found support that local kinematic information forms the basis for skill-based differences in anticipation of stroke direction. They also pointed out that the type of information picked up is not directly linked to the observer’s own movement production. Instead, information is picked up that can be linked to the movement outcome of the observed agent and can facilitate anticipation. However, there is some debate in literature as to what constitutes relevant information for anticipation. It has been suggested that single joint movements can provide anticipatory information for example for goal keepers anticipating kicking direction in penalty kicks (McMorris & Colenso, 1996). More recently, anticipatory information has been argued to be distributed across the movement multiple segments (e.g., Bourne, Bennett, Hayes, Smeeton, & Williams,

\[4\] Note that – like global – the label ‘local’ is used in various contexts in the literature. For the purpose of this thesis, local information refers to both isolated and distributed local information (Diaz, Fajen, & Phillips, 2012) as can potentially obtained from limb movements.
2013; Huys et al., 2009). More specifically, Diaz et al. (2012) examined the reliability of specifically these isolated or distributed forms of local motion information in the football penalty kick. The authors found that when predicting kicking direction, the more reliable anticipatory information is provided distributed over a number of segments (i.e., legs and elbows) rather than by a single joint as suggested by other research. As an alternative to global motion information, it seems clear that relative motion (at least as available from point-light displays) has also been found to provide relevant information for action when anticipating another agent’s actions. Anticipatory action might be advantageous in back-and-forward follow-the-leader coordination, given that each turnaround point (i.e., a direction change\(^5\)) of the leader is a critical event that would benefit from being anticipated as early as possible.

Depending on the task, an agent’s ability to anticipate upcoming actions can facilitate distance regulation. As such, followers may attune to information that does not directly specify distance (e.g., \(d\)), but instead provides information about upcoming critical events. In back-and-forward follow-the-leader coordination such pivotal events occur every time the leader changes direction. If the follower does not respond immediately at such a turnaround point, the distance between follower and leader can abruptly change, which would result in a temporary, though large, error in task performance. To compensate for such errors, followers can adopt a strategy that incorporates more or less anticipatory coupling based on salient information sources which allow for early detection of upcoming changes. It is likely that followers perceive information that allows for quicker responses. The only indication for an upcoming turnaround point that can be derived from the change in visual angle is a decrease in the rate of visual angle that occurs prior to a turnaround point. In a follow-the-leader task however, such deceleration of the visual angle has to be sufficiently large to reach discrimination threshold in order to be able to be picked up (Regan & Hamstra, 1993). Alternatively, segmental (i.e., local) motion information could provide important temporal information about the gait-cycle which could be used to anticipate upcoming actions. That is, changes in direction imply altered inter-segmental patterns to decelerate the centre of mass, for instance, by slightly tilting the trunk and altering the placement of the stance leg. Furthermore, it has been shown that the preparatory movements of a tennis server can provide

---

\(^5\) The terminology ‘turnaround point’ was chosen over ‘direction change’ to avoid confusion when movement direction is discussed. A turnaround point refers to the point where the leader changes direction for example from walking forwards to walking backwards. It does not imply that the leader ‘turns around’, as within a trial the leader will always keep facing in one direction.
anticipatory information about the serve direction (Canal-Bruland et al., 2011). In other words, local information can be accessed to anticipate global movements.

2.1.4 Aims and hypotheses

The aim of the present study was to examine how the global motion information affects coordination in a follow-the-leader task in comparison to a combination of global and local motion information. The hypotheses were examined by determining the degree to which the follower nulled the rate of change of the visual angle (i.e., maintained a constant distance: spatial accuracy; \( \dot{\alpha} \)), the point-estimate relative phase (\( \varphi \)) and the response times at each turnaround point (\( RT \)). Because expansion-compression information has been shown to specify action in a variety of discrete coordination tasks (Hristovski et al., 2006; Regan & Gray, 2000; Savelsbergh et al., 1991), for the current study it was hypothesized this generalizes to a continuous coordination task. It is expected that global visual information alone will be sufficient to allow accurate distance regulation in a continuous task. It is therefore hypothesized that the availability of local (i.e., limb movement) and global (i.e., expansion-compression) motion information will not alter spatial accuracy (no change in \( \dot{\alpha} \)) compared to global motion information alone. Additionally, when both local and global sources of motion information are present the temporal synchrony between follower and leader (less negative \( \varphi \)) would be tighter compared to when only global information sources are available, as there is potentially more information about upcoming actions.
Figure 2.1: Experimental setup: avatar condition (top) and sphere condition (bottom).
2.2 Methods

2.2.1 Task

Participants performed a follow-the-leader task, attempting to maintain a constant distance from a ‘leader’ that appeared in two different forms (see Figure 2.1). In the first condition, a life-size animated receding and approaching avatar presented local as well as global motion information. In the second condition, an approaching and receding animated sphere (similar in height to the avatar) provided solely change in visual angle as an indication of its virtual displacement. The participants were not instructed on how to maintain distance; it was only emphasized that they maintain the perceived initial distance from the leader. The starting position was fixed at 3.20 m from the projection screen. The leader would appear with the same projection size at the start of each trial, thus representing the same initial virtual distance in each trial. Movement of both the avatar and sphere were animated based on pre-recorded movements of the leader participant (see Section 2.2.3), ensuring typical acceleration and deceleration patterns of gait were matched between conditions.

2.2.2 Participants

Thirty-four healthy males (see Table 2.1) volunteered to participate as ‘followers’. No participant reported any motor or sensory impairment. Participants actively participated in a range of recreational sports. Ethical approval was obtained from University of Otago human ethics committee (12/339) prior to data collection.

Table 2.1: Descriptive characteristics (mean ± SD) of participants \((n = 34)\) and the projected leader.

<table>
<thead>
<tr>
<th></th>
<th>Participants</th>
<th>Leader</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age ((years))</td>
<td>28 ± 6.0</td>
<td>24</td>
</tr>
<tr>
<td>Weight ((kg))</td>
<td>81 ± 10.7</td>
<td>83</td>
</tr>
<tr>
<td>Height ((cm))</td>
<td>178 ± 18.6</td>
<td>188</td>
</tr>
<tr>
<td>Exercise ((hrs/week))</td>
<td>6 ± 4.4</td>
<td>12</td>
</tr>
<tr>
<td>Self-rated level of fitness ((1 \text{ low} - 10 \text{ high}))</td>
<td>6 ± 1.2</td>
<td>8</td>
</tr>
</tbody>
</table>
2.2.3 Apparatus & model recording

First, the stimulus data (i.e., the leader model) had to be created. For this reason, three-dimensional movement data of a back-and-forth walking person were recorded using a 10-camera Motion Analysis System (Vicon Motion Systems, Inc., Centennial, CO) at a sampling frequency of 200 Hz. Movement kinematics of this person (i.e., the leader) were reconstructed using a 15-segment model, with in total 50 reflective markers at each joint and on each segment. The trajectories of these markers were used to create the leader videos (Figure 2.1) with Autodesk’s MotionBuilder (Autodesk Inc., San Rafael, CA, 2013). A total of 25 different leader trajectories were generated. Each trial had a duration of 25 s, of which the first three seconds were performed stationary in the T-pose (i.e., with both arms extended laterally) for data processing purposes. The leader was in motion for a total of 22 seconds for each trial. The leader was instructed to walk back and forth within the measurement volume (6 x 2 x 2 m) at his preferred velocity. The regularity of the time between turnaround points was unspecified prior to data collection. On average, the leader changed direction every 2.10 ± 0.80 s.

In the experiment proper, the virtual movements of the leader were projected on a large 4 x 4 m screen with a Panasonic LCD PT-LB20 projector (resolution 1024 x 768 pixels, 2000 Lm) to produce a life-size image. The kinematics of the follower participants were recorded with the same motion analysis setup as described above for the leader using a simplified 15 marker model.

2.2.4 Procedure

After being informed of the study requirements, participants provided informed consent. The participants were prepared for data collection by attaching retro-reflective markers to record movements of the head, hands and feet. Similar to Ducourant et al. (2005) head markers were used as an indication of the whole-body displacement of participants. Furthermore, head markers were used to estimate eye height for the determination of visual angle (see Figure 2.2). For each participant, a total of 44 experimental trials were recorded. The conditions (i.e., sphere and avatar, see Figure 2.1) were presented in randomized blocks. Participants completed 3 practice then 22 experimental trials for each condition. Additionally, regular breaks were introduced in order to limit any fatigue effects, although intensity of the task was
considered light. After each condition, participants were asked to indicate their perceived rate of success using a slider bar ranging from easy to difficult.

![Diagram showing visualization of angle alpha]  
Figure 2.2: Visualization of $\alpha$. Note that the same object (i.e., leader) at a smaller distance would be observed with a larger $\alpha$. The horizontal axis directly represents $x_F$, and $y_F$ is visualized as the follower’s eye height.

2.2.5 Data reduction

Anterior-posterior movements were obtained from positional data for further analysis. All kinematic data were processed using MATLAB R2011a (The MathWorks Inc., Natick, MA, 2011). A piecewise cubic spline interpolation protocol was used to fill any gaps. Subsequently, movement data was filtered using a second order low-pass Butterworth filter with a cut-off frequency of 5 Hz.

2.2.6 Outcome measures

2.2.6.1 Spatial accuracy

This study employed a task in which participants follow the movements of a virtual leader that was video-projected on a flat screen. Hence, there is only a virtual distance between the follower and leader and no actual physical distance that could be quantified. Therefore, virtual distance regulation was quantified using the rate of change of visual angle ($\dot{\alpha}$). The visual angle ($\alpha$) was defined as the angle with the top and bottom of the projection at the observer’s eyes (see Figure 2.2) and calculated using the law of cosines:
\[
\cos(a(t)) = \frac{b(t)^2 + c(t)^2 - a(t)^2}{2b(t) \cdot c(t)} \ 
\text{Equation 2.1}
\]

where \(a(t)\) is the size of the projection, calculated as the difference between the top \((\text{top}(t))\) and the bottom \((\text{bottom}(t))\):

\[
a(t) = \text{top}(t) - \text{bottom}(t) \ 
\text{Equation 2.2}
\]

The on-screen resolution was 317 pixels/m. From the animations, the projection size in pixels could be obtained for each point in time, from which we could determine physical on-screen projection size \((a, \text{see Figure 2.2 and Equation 2.2})\) and the physical heights of \(\text{top}(t)\) and \(\text{bottom}(t)\) (i.e., in metrical units). Although the projected size was similar, the aforementioned process was done separately for the avatar and sphere conditions. Subsequently, the distance \(b(t)\) between the follower’s eyes and the top of the projection of the leader was calculated using the follower’s horizontal distance to the screen \((x_F(t))\) and the vertical position of the eyes \((y_F(t))\) in relation to the top of the projection \((\text{top}(t))\):

\[
b(t)^2 = x_F(t)^2 + (y_F(t) - \text{top}(t))^2 \ 
\text{Equation 2.3}
\]

and finally the distance \(c(t)\) between the follower’s eyes and the bottom of the projection, calculated similar to \(b(t)\):

\[
c(t)^2 = x_F(t)^2 + (y_F(t) - \text{bottom}(t))^2 \ 
\text{Equation 2.4}
\]

Distances \(a(t), b(t)\) and \(c(t)\) are all in meters and \(a(t)\) is the visual angle in degrees. This visual angle is sensitive to the follower’s head height \((y_F(t))\), the distance to the screen at the time of the projection \((x_F(t))\) and the projection size of the shape presented \((a)\). Subsequently the rate of change in visual angle \((\dot{a}(t))\) was obtained by numerically differentiating \(a(t)\). Note that the relationship between distance and \(a\) is inverse and tangential. An increase in distance translates to a decrease in \(a\). However, when the distance is doubled, \(a\) is not necessarily halved (see for more detail, Figure 2.6). This relationship depends on the ratio of the distance to and the size of the perceived object.
In Figure 2.3, an example can be seen of how \( \dot{\alpha} \) typically develops over time. In fact, the task instruction implied keeping \( \dot{\alpha} \) at 0 deg·s\(^{-1}\), as that would indicate the visual angle does not change over time and, hence, the (virtual) distance to the leader would not change. Theoretically, if the task was executed perfectly \( \dot{\alpha} \) would be equal to 0 deg·s\(^{-1}\) at every time point. To quantify the extent to which this was achieved, three error measures were determined (see Section 2.2.6.2). Furthermore, to test whether the movement direction of the leader significantly influenced the spatial accuracy, \( \dot{\alpha} \) was analysed separately for the approaching and receding movement directions of the leader. That is, when the leader form was expanding (i.e., moving towards the follower) \( \dot{\alpha} \) was categorized as ‘approaching’ and when the leader form was contracting (i.e., moving away from the follower) \( \dot{\alpha} \) was categorized as ‘receding’. In Figure 2.3 the leader’s movement direction is indicated with a lighter (receding) or darker (advancing) background colour.

![Figure 2.3: Exemplary data of one trial and its within-trial CD \( \dot{\alpha} \) (see Section 2.2.6.2) showing a typical profile of the rate of change in visual angle (\( \dot{\alpha} \)) in degrees per second. ‘Receding’ (light grey) and ‘approaching’ (dark grey) indicate the leader’s movement direction.](image-url)
2.2.6.2 Temporal synchrony

The temporal synchrony between the leader and the follower was assessed by response times (RT), implying the time (in ms) between a turnaround point of the leader and the corresponding turnaround point of the follower. A custom algorithm determined any change of direction in the positional data that exceeded the arbitrary minimum of 0.3 m. A visual check determined if the algorithm functioned adequately. In terms of synchrony, an RT of 0 ms would indicate a perfect temporal synchrony. Negative values indicate anticipatory turnaround points (i.e., follower changes direction before the leader) and positive values quantify the magnitude of delay in followers’ response.

Although RT as defined above provides a clear measure of temporal synchrony, it only informs about the synchrony in terms of time. The point-estimate relative phase (φ) was additionally calculated as it informs about temporal synchrony in terms of cycle phase (i.e., related to the cycle period). Typically, the point-estimate (or: discrete) relative phase is an amplitude-independent measure of synchrony between two oscillating components. To calculate φ, first the period (in s) of the ith movement cycle was determined for both leader and follower separately:

\[
Period(i) = t_{end}(i) - t_{start}(i)
\]

Equation 2.5

where \(t_{start}\) refers to the start and \(t_{end}\) the end of the ith movement cycle. Each turnaround point was defined as a start of a movement cycle (\(t_{start}\)) and the end of that movement cycle is the next turnaround point in the same direction as at \(t_{start}\) (i.e., each period has a turnaround point in the other direction roughly half-way). Subsequently, for each period the moment of half-way point (MidPeriod) of each cycle was determined for the leader and follower separately:

\[
MidPeriod(i) = t_{start}(i) + \frac{1}{2} \cdot Period(i)
\]

Equation 2.6

Then, the Lag (in s) of the ith MidPeriod of the follower in relation to the corresponding ith MidPeriod of the leader was determined:

\[
Lag(i) = MidPeriod_f(i) - MidPeriod_L(i)
\]

Equation 2.7
where the subscript $F$ indicates the follower and the subscript $L$ the leader. Note that a negative $Lag$ indicates a lagging follower, whereas a positive $Lag$ indicates that the follower is ahead of the leader. Finally the point-estimate relative phase ($\varphi$) for the $i^{th}$ movement cycle was calculated in radians as:

$$\varphi(i) = \frac{Lag(i)}{\text{Period}_L(i)} \cdot 2\pi$$

Equation 2.8

where $\text{Period}_L$ (in seconds) indicates the duration of the $i^{th}$ period of the leader. The discrete relative phase was chosen over a continuous relative phase as a continuous relative phase would not be able to effectively deal with missed turnaround points as became evident through pilot work.

$\varphi$ (rad) is thus a measure of temporal synchrony throughout a trial between the leader (reference signal) and follower. This holds information about the mode of coordination, which could be anywhere between in-phase ($0 \cdot \pi$ or $2 \cdot \pi$ rad) and anti-phase ($-\pi$ or $\pi$ rad). For the current task, participants aim to achieve a phasing of $0$ rad ($CD \ varphi$, see Section 2.2.6.2), indicating perfect temporal synchrony. Furthermore, $\varphi$ provides an insight of the temporal synchrony between turnaround points throughout a trial. The error measures (see Section 2.2.6.2) quantify the consistency (i.e., $VE \ varphi$) and the accuracy (i.e., $AD \ varphi$) of the lead-lag relationship. To subject $\varphi$ to statistical analysis its error measures (see Section 2.2.6.2) will be determined using circular statistics (Berens, 2009; Burgess-Limerick, Abernethy, & Neal, 1991).

### 2.2.6.3 Error measures

Both $\dot{\varphi}$ and $\varphi$ are obtained as time-series. The development of these variables over time holds important information about how follow-the-leader coordination evolves. The following three error measures were deemed appropriate to accurately describe the outcome. First, the constant deviation ($CD$) was calculated as the average deviation from the target ($x_{\text{target}}$) of the outcome variable ($x(t)$) over time (within one trial). Note that for both $\varphi$ and $\dot{\varphi}$ the target value was zero, as a value of zero for $\varphi$ and $\dot{\varphi}$ would indicate perfect synchrony and distance keeping with the leader. As such, $CD$ in this case simply equals the average value for $\varphi$ and $\dot{\varphi}$ within a trial, and reflects the degree and direction of the deviation from the target value. Subsequently, the variable error ($VE$) was determined as the within-trial standard deviation.
Finally, the average absolute deviation ($AD$) informs about the accuracy with which the target is maintained:

$$AD = \sum_{t=1}^{n} \frac{|x(t) - x_{\text{target}}|}{n}$$  \hspace{1cm} \text{Equation 2.9}

where $x(t)$ is the outcome measure (i.e., $\varphi$ or $\dot{\alpha}$) at each time point, $x_{\text{target}}$ the aimed value of $x(t)$ and $n$ the total number of time points analysed. Given that $x_{\text{target}}$ for both outcome measures in the current study is zero, Equation 2.9 can be simplified as:

$$AD = \sum_{t=1}^{n} \frac{|x(t)|}{n}$$  \hspace{1cm} \text{Equation 2.10}

For $\varphi$ negative $CD$ values indicate that on average the follower was phase lagging the leader. Positive values would indicate that the follower was ahead of the leader. $VE \varphi$ informs on how stable this lead-lag relationship was. High values would indicate an ever-changing lead-lag relationship, whereas low values would indicate that the relationship is consistent. Finally, $AD \varphi$ informs on the accuracy of the leader-follower coordination. As the aim of each participant was to keep the same distance and coordinate perfectly in-phase (i.e., $\varphi = 0$ rad), any deviations from that aimed phasing are inaccuracies.

For $\dot{\alpha}$, keeping the distance implied to maintain a constant visual angle (i.e., $\dot{\alpha} = 0$ deg·s$^{-1}$). A negative $CD \dot{\alpha}$ indicates that throughout the trial the leader form was mainly receding. Positive values indicate the opposite: an approaching leader form. Subsequently $VE \dot{\alpha}$ informs about how variable this contraction-expansion relationship was. $AD \dot{\alpha}$ finally informs about how accurately it was maintained. Put simply, $CD$ can be considered as the lead-lag relationship, $VE$ as the consistency, and $AD$ as the accuracy of the outcome measure it relates to.

### 2.2.7 Statistical analysis

A total of 26 trials were excluded due to technical problems (i.e., missing data). The remaining 1,496 trials were analysed. For each participant ($n = 34$) outcome measures were first averaged across all included trials for each condition. Subsequently, paired samples $t$-tests and RM ANOVAs were run (using SPSS version 21.0, IBM Corp., New York, Armonk, NY, 2012) to test for significance of potential effects of shape (avatar or sphere), direction
(approaching or receding) and interactions between these two factors. For the RM ANOVAs, a Greenhouse Geisser correction factor was applied for any violations of sphericity and Bonferroni corrections were applied for post hoc $t$-test comparisons.

## 2.3 Results

### 2.3.1 Trial characteristics

Before the results of the main outcome measures are presented, general locomotion characteristics are presented. In Table 2.2 an overview is given of the characteristics of the movements of both leader and follower separately. Note that the leader characteristics are the same in both conditions (avatar, sphere). Therefore, these measures of the leader participant are only provided as a reference and not included in any of the statistical comparisons. It can be noted however that the leader seemed to cover more distance than the leader, take more steps, and have a larger velocity. Ducourant et al. (2005) Paired samples $t$-tests showed the number of steps taken by the participants was significantly larger in the avatar condition compared to the sphere condition (see Table 2.2, $t(33) = 3.853, p = 0.001$).

The self-reported rate of success showed no significant difference between the avatar ($71 \pm 18\%$) and sphere ($67 \pm 16\%$), indicating that participants were unaware of any spatio-temporal difference between conditions that have existed.
Table 2.2: Mean and standard deviation of the locomotion characteristics for the different leader and follower are indicated with ‘L’ and ‘F’, respectively.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Avatar</th>
<th>Sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travelled distance (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>14.08</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>11.34 ± 1.53</td>
<td>11.20 ± 1.60</td>
</tr>
<tr>
<td>Number of steps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>39.36</td>
<td></td>
</tr>
<tr>
<td>F*</td>
<td>35.75 ± 2.92</td>
<td>33.49 ± 5.14</td>
</tr>
<tr>
<td>Head velocity (m·s⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Approaching Leader</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.54 ± 0.08</td>
<td>0.52 ± 0.08</td>
</tr>
<tr>
<td>Receding Leader</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.57 ± 0.07</td>
<td>0.56 ± 0.07</td>
</tr>
</tbody>
</table>

* Significant condition effect (p < 0.05)

2.3.2 Spatial accuracy

In Figure 2.4 the main results of each measure are displayed. For CD $\alpha$ significant main effects for both condition ($F(1,33) = 27.156, p < 0.001, \eta^2_p = 0.451$) and direction ($F(1,33) = 31.723, p < 0.001, \eta^2_p = 0.490$) were observed. $CD \alpha$ was closer to zero averaged across directions in the sphere condition (mean ± SD = 0.11 ± 0.02 deg·s⁻¹) compared to the avatar condition (mean ± SD = 0.18 ± 0.03 deg·s⁻¹). Averaged across avatar and sphere conditions, estimated means for direction infer that $CD \alpha$ was higher and positive when the leader approached the follower (mean ± SD = 0.82 ± 0.11 deg·s⁻¹) compared to when the leader receded (mean ± SD = -0.52 ± 0.13 deg·s⁻¹). This direction effect appears consistent for both conditions given the absence of a significant condition-direction interaction. To illustrate this effect, in Figure 2.3 an example can be seen of how $\alpha$ typically develops over time, including

Note: Distance and velocity for the leader is based on the original model recording and therefore does not necessarily truthfully represent the velocity as specified by the virtual display. Furthermore, because of the averaging procedure across trials for each participant, a meaningful standard deviation of the leader’s characteristics could not be calculated (i.e., the leader is the same for each participant so the standard deviation would be zero).
the effect of direction. It appears that in terms of $\dot{\alpha}$, the leader-follower relation is more erratic around each turnaround point (given the large deviations from the targeted value of $\dot{\alpha}$ in Figure 2.3), followed by a more or less stabilizing period in between turnaround points.

For $VE\,\dot{\alpha}$ the main effect for direction was significant ($F(1,33) = 42.152, \, p < 0.001, \eta_p^2 = 0.561$). $VE\,\dot{\alpha}$ is smaller when the leader is moving towards the follower (mean $\pm$ SD = 2.15 $\pm$ 0.12 deg·s$^{-1}$) than vice versa (mean $\pm$ SD = 2.31 $\pm$ 0.11 deg·s$^{-1}$). Furthermore, the condition-direction interaction was also significant ($F(1,33) = 12.105, \, p = 0.001, \eta_p^2 = 0.268$). To further explore this interaction effect, paired samples $t$-tests were run on direction for each condition separately. It was revealed that only for the sphere condition $VE\,\dot{\alpha}$ increased significantly when the leader was receding ($t(33) = 4.431, \, p < 0.001, \, d = 0.92$). No significant post-hoc effect was found for the avatar condition. For $AD\,\dot{\alpha}$ only the interaction effect was significant ($F(1,33) = 28.389, \, p < 0.001, \eta_p^2 = 0.462$), although there was a trend ($p = 0.09$) for a main effect of direction. Post-hoc tests revealed that both for the avatar ($t(33) = 2.788, \, p = 0.009, \, d = -0.54$) and sphere ($t(33) = 8.420, \, p < 0.001, \, d = -1.63$) condition participants had a larger $AD\,\dot{\alpha}$ when the leader was receding compared to approaching. Subsequently, the interaction effect resides in participants in the sphere being affected more strongly than in the avatar condition (see Figure 2.4, right panel).

Figure 2.4: Means ± SD for the three error measures of $\dot{\alpha}$. Significant condition effects (*), direction effects (+) and condition-direction interaction effects (Δ) are indicated in the graph. The interaction effect was significant for both $VE\,\dot{\alpha}$ and $AD\,\dot{\alpha}$.
2.3.3 Temporal synchrony

Followers was found significantly less accurate in maintaining in-phase coordination ($AD \varphi$) in the sphere condition compared to the avatar condition (see Table 2.3), $t(33) = 2.342, p = 0.025, d = 3.6$. Neither the average lead-lag relation ($CD \varphi$), nor the variability of the coordination ($VE \varphi$) was observed to be significantly affected by condition.

<table>
<thead>
<tr>
<th></th>
<th>Avatar</th>
<th>Sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CD \varphi$ (rad)</td>
<td>-0.38 ± 0.53</td>
<td>-0.46 ± 0.52</td>
</tr>
<tr>
<td>$VE \varphi$ (rad)</td>
<td>0.34 ± 0.19</td>
<td>0.34 ± 0.25</td>
</tr>
<tr>
<td>$AD \varphi$ (rad)</td>
<td>0.57 ± 0.12</td>
<td>0.61 ± 0.13</td>
</tr>
</tbody>
</table>

*Significant difference between avatar and sphere ($p < 0.05$)

In Figure 2.5 the response times ($RT$) at each moment where the leader changed direction (i.e., a turnaround point) are displayed for the two conditions averaged across participants. Averaged across all within trial turnaround points, $RT$ was larger in the sphere condition (mean ± SD = 93.69 ± 33.8 ms) compared to the avatar (mean ± SD = 77.06 ± 28.0 ms), $t(33) = 2.465, p = 0.019, d = 1.93$. Subsequently, the turnaround points within each trial were subjected to a 2 (condition) x 10 (turnaround point) RM ANOVA. Only the first 10 turnaround points of each trial were included as that was the minimum number of turnaround points that occurred in a trial. In contrast to the $t$-test for the average $RT$, the main effect for condition was not significant ($p = 0.052$) when including the $RT$ at the level of each turnaround point. However, significant effects were observed for both a main effect for turnaround point ($F(9,297) = 22.443, p < 0.001, \eta_p^2 = 0.405$) and an interaction effect between condition and turnaround point ($F(9,297) = 12.214, p < 0.001, \eta_p^2 = 0.270$). Figure 2.5 suggests that this interaction effect resides in the difference between the first ‘turnaround point’ (i.e., movement initiation) in contrast with the remaining turnaround points. A closer inspection of this interaction was conducted using difference scores (avatar – sphere) for each turnaround point. A 10-level RM ANOVA was conducted using these difference scores revealed a significant main effect for turnaround point ($F(9,297) = 12.213, p < 0.001, \eta_p^2 = 0.270$), indicating the difference between conditions was not the same for each turnaround point. Most notably, post hoc comparisons indicated the difference score for the first turnaround point was significantly changed compared to 8 out of 9 following turnaround.
Follow the leader

points ($p’s < 0.05$) (see Figure 2.5). Participants had a lower $RT$ in the sphere condition compared to the avatar condition at the movement initiation, whereas in the remainder of the trial (i.e., turnaround point 2-9) $RT$ was lower in the avatar condition.

Figure 2.5: Follower’s response times for the different conditions at the initiation of the movement (1), at the subsequent turnaround points (2 – 10), and averaged across all turnaround points. The turnaround points for which the difference between conditions is significantly different from the initiation of the movement (*) and the overall effect for condition (Δ) are indicated.

2.4 Discussion

The primary aim of the present study was to examine how following a forward-backward moving avatar differed from following a forward-backward moving sphere. Overall, the spatial accuracy (as indexed by results of $\hat{\alpha}$) was better maintained in the sphere condition compared to the avatar condition. Furthermore, a strong effect was found for movement direction of the leader (approaching or receding) on $\hat{\alpha}$, which mostly affected leader-follower coordination in the sphere condition. Regarding the accuracy of the temporal synchronization ($AD \varphi$), the follower’s performance was significantly more accurate in the avatar condition.
compared to the sphere condition. This was further corroborated by significantly lower $RT$ in the avatar condition. Together these results indicate that isolating global motion information decreases the temporal synchrony between follower and leader, but the spatial accuracy may in fact benefit from the isolation of this information.

### 2.4.1 Temporal synchrony

In line with expectations, the relative phasing was more accurate (indicated by $AD\,\varphi$) in the avatar condition. Given that the instructed in-phase coordination did not differ in variability ($VE\,\varphi$) between the sphere and avatar condition, the observed difference in $AD\,\varphi$ might be due to a systematic lead-lag difference between conditions. However, the effect of condition on $CD\,\varphi$ was not significant. The relative phasing was thus more accurate in the avatar condition without significantly affecting the lead-lag relationship. Arguably, such increased accuracy of the temporal synchronization of distance regulation could be crucial in heavily time-constrained settings as for example fencing or boxing. Furthermore, the response times at key events (i.e., the leader’s initiation of movement and subsequent turnaround points) were examined to explore the temporal aspect of the synchronization. Overall, the $RT$ was smaller in the avatar than in the sphere condition. Further analysis revealed however that the condition effect was not significant when looking at each turnaround point separately. A strong interaction effect with condition and $RT$ at the movement initiation compared to $RT$ at the subsequent turnaround points may have clouded the main effect for condition. Regardless, participants could generally respond faster at the turnaround points in the avatar condition. However at movement initiation the opposite effect was present. At the start of trials there was a larger response time in the avatar compared to the sphere condition. Perhaps the information provided by the avatar was too rich in comparison to the sphere, therefore making the additional information distracting, rather than informative. Over time however, the segmental information consistently allowed for more timely adaptation.

Arguably, these results indicated that global motion information was not sufficient for such fast responses. It is most likely that participants tune into some aspects of the local motion information available in the avatar condition that are not necessarily specifying in order to readily respond. For instance, a turnaround point may be preceded by a tilt of the body and/or a slight adaptation of foot placing. However, the benefit of attunement to segmental motion information has to be considered with care, as for example in sports the same information may be used to deceive opponents in order to gain an advantage. Brault et al. (2012) for
example found that rugby players attune to the more ‘honest’ global motion information when judging running direction after a deceptive side-step. Honest information refers to information that can only be specifying for the action it will be related to. That is, although the posture may inform about future actions, particularly in competition posture can also be used to deceive the opponent, therefore (potentially) displaying dishonest information. Optical size based information on the other hand is robust less likely to be deceptive. Information that has the potential to be used deceptively can also be termed non-specifying. In some situations this information does correlate with the specifying variable, but this is not always the case. As such, even though a temporal advantage may be gained from more local motion – non-specifying – information, at the same time it is less honest and can thus lead to incorrect anticipation. The most successful strategy may thus be to ignore the probabilistic (i.e., potentially incorrect, cf. Franchak & Adolph, 2014) local motion information, depending on the situation.

The extent to which probabilistic information is attuned to may depend on the risks of incorrectly versus correctly anticipating an action. Noël and colleagues argued that goal keepers face a striking example of such a risk dilemma during a penalty kick situation (Noël, van der Kamp, & Memmert, 2015). Goal keepers could wait until more honest information gives them increased certainty about the kicking direction, however, this often means that the goal keeper will not be able to dive towards the ball on time. Consequently, goal keepers are forced to make an anticipatory decision without such honest information. This implies that although there are multiple sources that can be useful for regulating behaviour (e.g., distance), some might be more appropriate at certain times than others, depending on the scenario. In sum it can be said that although segmental motion information provided clear advantages in terms of the temporal synchrony, it may be that the information that participants attuned to is rather non-specifying and not useful in every situation.

### 2.4.2 Spatial accuracy

The rate of change of the visual angle (\(\dot{\alpha}\)) has previously been shown to mediate following a leader in forward walking on a straight path (Rio et al., 2014). In the first part of their study, Rio and colleagues (Rio et al., 2014) showed that followers most likely adopted a speed-matching strategy when following a leader walking forward. In the second part of their study, they examined what information, either visual angle or binocular disparity, followers attune to when following a leader. They found that followers mostly relied on visual angle-based
information. In the current study it was found that followers consistently covered less distance than specified by nulling $\dot{\alpha}$. When the leader was moving towards the followers, participants consistently maintained a positive $\dot{\alpha}$, whereas when the leader was moving away, participants maintained a negative $\dot{\alpha}$. Note that this would also be true for a stationary ‘follower’, given the back- and forwards nature of the task. However, the relatively low error measures showed that participants did manage to null $\dot{\alpha}$. The error measures ($VE$ and $AD\dot{\alpha}$) revealed that in terms of nulling $\alpha$, participants were consistently (un)successful in each direction. The participants’ undershoot can be attributed to applying a conservative strategy in order to timely anticipate turnaround points. Although the turnaround points of the leader happen without (intentional) regularity, the leader’s movements are confined within a limited movement area. Therefore, participants may have partly anticipated turnaround points based upon the leader nearing the limits of the movement area. This could have facilitated a conservative strategy. Future research should incorporate more variation in regularity of the leader’s movement pattern, to see if participants adopt a less conservative strategy if the leader is less regular to explore the extent to which $\dot{\alpha}$ regulates follower behaviour.

In the sphere condition, the information presented was limited to global motion information. It was indeed found that, overall, $\dot{\alpha}$ was maintained closer to 0 deg·s$^{-1}$ in the sphere compared to the avatar condition. Interestingly, the condition-direction interaction showed that in the sphere condition the variability of the maintained pattern was more strongly affected by direction than in the avatar condition. When the leader approached the follower, the participants managed to maintain $\dot{\alpha}$ more stably than when the leader receded. The accuracy of $\dot{\alpha}$ further confirms this effect. Both conditions showed higher accuracy when the leader was moving towards the follower, but this effect presented itself more strongly in the sphere condition than the avatar condition. Perhaps the non-linear nature of $\alpha$ provides an explanation for this. (D. N. Lee, 1976) The relation to $\alpha$ and distance is more linear at larger distances due to the tangential relationship between relative position and $\alpha$ (and thus $\dot{\alpha}$). At smaller distance the relationship becomes exponential, as such, the smaller the distance, the larger the change in $\alpha$. In Figure 2.6 the change in $\alpha$ is shown for one step closer and one step further than the reference distance. Assuming a person of average height and a fixed step size (0.90 m), $|\alpha_{\text{closer}} - \alpha_{\text{ref}}|$ can be up to 50% larger than $|\alpha_{\text{further}} - \alpha_{\text{ref}}|$, where the subscript ‘ref’ indicates the starting position and ‘closer’ or ‘further’ indicates the direction in which a step is taken. Although this is simply a direct consequence of the tangential relationship between visual angle and distance, it does have important implications for any distance-
keeping strategies based on visual angle. It could, for example, explain the increased sensitivity to an increasing compared to a decreasing visual angle, found by Rio and colleagues (Rio et al., 2014).

![Figure 2.6: Visualization of the bias for direction in visual angle.](image)

This asymmetrical characteristic of visual angle implies that there is less information specifying relative position when the leader is receding, which may explain the worsened spatial accuracy. Alternatively, the direction of locomotion could play a role as well, since the leader’s locomotion direction is always opposite to the follower. That is, if the leader is approaching the follower, the leader is walking forwards whilst the follower is walking backwards. Nevertheless, the direction effect is weaker in the avatar condition, which suggests that participants managed to use other sources of information to keep the distance. This raises a question, however: what is it from the avatar that provides the additional information compared to the sphere condition? Perhaps followers managed to adopt a flexible perceptive strategy, relying on multiple sources of information (Abreu et al., 2012). The larger number of steps taken in the avatar condition compared to the sphere condition (whilst covering the same distance) could be interpreted as a way to more accurately fine-tune locomotion while allowing for increased adaptability. It is interesting to note, however, that although there were some clear differences in follower coordination between conditions, participants were apparently unaware of this given their self-reported success rate.
Although many forms of information could (partially) inform about relative position, it is most likely the complementary nature of a number of sources of information that allows for tighter temporal synchronization in the avatar condition. Given that visual angle information is more or less specific depending on the circumstances at that time, it is possible that the same is true for other sources of information. Based on the current study, it is suggested that information for action in a distance-keeping task is not dichotomous; rather, it is divided in a range of possibly specifying sources along a spectrum from local (i.e., segmental motion information) to more global (i.e., expansion-compression) information. Keeping distance in a cyclical task may be directly specified by perception of the visual angle, since both conditions were consistent in under- and overestimating the displacement. This extends the use of visual angle from, for example, catching balls, aligning headings and avoiding collisions (Bruggeman, Zosh, & Warren, 2007; Pinheiro Menuchi & Bucken Gobbi, 2012; Savelsbergh et al., 1991) to keeping distance in a follow-the-leader task. Although given the effect of movement direction on $\hat{a}$, the degree of specification of visual angle may not be universal and related to the direction of the movement.

### 2.4.3 Conclusion

The cyclical whole-body coordination task employed in this study has provided support for the idea that a follow-the-leader task can be partially guided by visual angle information alone (cf., discrete interceptive tasks; cf., Fajen & Warren, 2007; Rio et al., 2014; Savelsbergh et al., 1991; Warren et al., 2001). However, coupling does not only happen at a global level; local information was also found to influence coordination given the effect of condition. A flexible use of specifying information at the right time could explain the differences between conditions. It appears that the local information available in the avatar condition is mainly beneficial at the turnaround points. In sum, although local information is not pivotal for spatial accuracy, there is a clear advantage in temporal synchrony which may be of particular importance in heavily time-constrained settings such as in invasion sports.
Chapter 3

A Proposed Spectrum

Perception-Action Coupling for Follow the Leader Coordination: a Proposed Spectrum from Local to Global Motion Information
3.1 Introduction

Humans can coordinate their movements with each other efficiently in complex and dynamic situations. For example, on a daily basis humans can navigate successfully through crowds of people, drive a car through traffic, or play sports. In many situations, there are no (obvious) rules or constraints that determine how interpersonal coordination emerges. Instead, some less tangible constructs (e.g., social norms, mood, or skill) may dictate how behaviour unfolds. In sports, interpersonal interactions can arguably be linked to each individual’s skill at interacting effectively with others – their ‘interact-ability’ (Meerhoff & De Poel, 2014). Through visual and motor experience, humans learn to satisfy mutual goals by attuning to information presented by others and calibrating their actions accordingly (Fajen, Riley, & Turvey, 2009; Le Runigo et al., 2005; Sebanz & Shiffrar, 2009; Weissensteiner, Abernethy, & Farrow, 2011). The present study explores how different information sources are exploited to jointly coordinate back-and-forth locomotion.

In the motor control literature, it has been argued that the visual angle (or a related variable, e.g., Tau), holds sufficient specifying information for movement regulation in numerous interceptive tasks (e.g., D. N. Lee, Georgopoulos, Clark, Craig, & Port, 2001; Regan & Gray, 2000). As interception is a form of distance regulation, in Chapter 2 it was hypothesized that information based on the visual angle may also play an important role in back-and-forth follow-the-leader coordination (see also, Rio et al., 2014). In Chapter 2, participants attempted to follow the movements of a virtual ‘leader’, who presented a degree of potentially specifying information. In the high specifying condition, the leader was an avatar reconstructed from a human’s gait. In the low specifying condition, the leader was a sphere that expanded and contracted at a rate matched to the avatar. The findings suggested that people were able to maintain distance with both types of leader. Although high specifying information resulted in a tighter temporal synchronization, it appeared to disrupt the spatial accuracy (i.e., constant deviation of visual angle velocity further from the target). The low and high specifying conditions are arguably the two extremes of a potential continuum of useful information for action. Which aspects of this continuum are necessary for both temporal synchronization and spatial accuracy is examined in this follow-up study.
3.1.1 A proposed spectrum: from local to global

The current study aimed to extend upon the findings of Chapter 2 by investigating a proposed spectrum of potential information sources which allow a follower to coordinate with a leader. In Chapter 2 it was found that both local and global motion information may play an important role in regulating distance. Local information refers to the relative information of the segments (i.e., limbs) of a person in motion (cf., local or relative motion information, Roca et al., 2011). Global motion on the other hand refers to the information from an object in relation to its environment, such as expressed by the optical expansion rate (Durgin & Li, 2011; Ito & Matsunaga, 1990; Regan & Gray, 2000). When coordinating one’s actions with another person in real life, both of these extremes are accessible in combination (Fine, Likens, Amazeen, & Amazeen, 2015). To provide a more complete theory on what information is used for action when regulating distance, it is important to consider that there may be a variety of alternative information sources that are attuned to when regulating distance. The current chapter will therefore examine if the information for action may sit along a spectrum from local to global motion information. In the following sections, the spectrum will be further introduced and justified (see Figure 3.1 for a visual representation). The spectrum is proposed to provide local motion information through limb movement, information about cadence through vertical and horizontal sway and lastly global motion information through the displacement related expansion and retraction.

As put forward in the previous chapter, pertinent information for regulating distance can be obtained from local information sources. A person’s posture, step pattern or trunk orientation can inform about upcoming actions (Brault et al., 2012). Note that local motion information in this study refers to information that can be localized at the segmental level. In the movement sciences segmental motion information has been studied in isolation using point-light displays (Johansson, 1973, 1976). The relative motion of each segment is emphasized by a point-light for each joint and segment. A point-light display is not entirely without expansion-compression however, as the point-lights loom in relation to each other. Nevertheless, it is presumed that most attention of the followers will be drawn to the segmental motion in a point-light display. At the very least, a point-light display draws the attention to segmental motion, hence providing more inviting affordances (Withagen, de Poel, Araújo, & Pepping, 2012) from the segmental motion compared to the looming. Segmental motion information inevitably provides information in the form of for example stride length and rate, but also
postural change and balance (Sartori et al., 2011). Stride length and rate are spatial and temporal parameters that together provide an accurate image of the spatiotemporal characters of gait (Dugan & Bhat, 2005).

In addition to – or combination with – the segmental motion information, information about a person’s cadence may also provide an important source of information for regulating distance. Cadence is characterized by lateral and vertical sway, albeit quite subtle. It specifically refers to the number of strides per unit of time (i.e., the rhythm or stride rate), thus informing (and indirectly predicting) about displacement. In running, it has been shown to relate to efficiency and fluency of locomotion (Bood, Nijssen, van der Kamp, & Roerdink, 2013; Varlet & Richardson, 2015). In fact, cadence has been shown to correlate significantly with a number of general gait parameters (e.g., speed, stride length, and stance phase duration, see Funato, Aoi, Oshima, & Tsuchiya, 2010; Kirtley, Whittle, & Jefferson, 1985). So it can be surmised that some specifying information may be captured in the cadence of gait. Furthermore, it has been observed that people synchronize their cadence when walking side-by-side (Nessler & Gilliland, 2010; Nessler, Gutierrez, Werner, & Punsalan, 2015). Therefore, this study examined if the perception of cadence-related information may indeed facilitate the perception-action coupling in follower-leader coordination.

There is indicative evidence that a follower may apply the strategy of nulling optical expansion in order to match the speed of a leader (Rio et al., 2014), which would mean that any shape showing a change in optical size related to its displacement can provide sufficient information for this task. For a variety of tasks, humans have been shown to be very sensitive to such a global source of information. For example, when catching illuminated balls in the dark, humans were found to accurately change hand aperture as directly specified by the optical expansion (i.e., visual angle change as a result of displacement and physical size change; see Savelsbergh et al., 1991). Furthermore, Brault et al. (2012) inferred that defenders, when attempting to intercept an attacker, can judge an attacker’s final running direction using global motion information (i.e., ‘tau-based’ information about the centre of mass). They also showed that compared to novices, experts manage to guide their actions predominantly by the global motion information when defending an attacker that aimed to deceive the defender. Attackers use deceptive movements to draw the attention away from ‘honest’ signals (i.e., centre of mass) to more ‘dishonest’ signals (i.e., trunk or head
Follow the leader

movement). ‘Honest’ information is thus necessarily related to the movement outcome, whereas dishonest – or deceptive – information is not (Johnstone, 1994; Stuart-Fox, 2005). It was surmised that global motion information provided the most honest information about the attacker’s intended direction. For follow-the-leader coordination, this may mean that changes in visual angle will be a (more) reliable source to regulate distance, that is, visual angle (of the leader as a whole) will always specify distance and cannot be used deceptively.

3.1.2 Key task constraints

In addition to the types of information presented on the proposed spectrum, there are several task constraints that could influence how these information sources were used for action. One constraint is the viewpoint from which the leader is observed. In the previous study (Chapter 2), the follower was always facing the leader. In other words, a receding leader was walking backwards as the follower was walking forwards and vice versa for an approaching leader. Interestingly, in the sphere condition of Chapter 2, the coordination seemed to be least consistent when the leader was walking backwards – or receding. This effect was attributed to the asymmetrical relationship between visual angle and distance. However, it was not excluded that the mismatch in walking direction (i.e., forwards or backwards) between the follower and leader resulted in a movement direction (i.e., receding or approaching) effect. Although the movements are similar, backwards walking is not simply a reversed model of forwards walking (Grasso, Bianchi, & Lacquaniti, 1998). In fact, the movement characteristics of backwards walking have been shown to be different from forwards walking in terms of, for example, step velocity and stride length (Ducourant et al., 2005). As such, the direction-related variability of Chapter 2 may be attributed to a mismatch in walking direction between follower and leader.

Another important factor which might influence perceptual strategy is the predictability of the leader’s movements. For the current task, one aspect of the predictability can be captured in the regularity of the interval lengths between leader’s turnaround points. Arguably, with more regular intervals between turnaround points, followers can adapt to the rhythm of the pattern rather than having to respond to (real-time) motion information. However, when the leader’s movements are less regular – and thus less predictable – real-time adaptation will be more important for timely coordination, as the leader’s movements constantly have to be considered to adjust one’s own movements. Therefore, the intervals between turnaround points of the
leader are systematically manipulated in the current study. Note that predictability in general encompasses more than just the rhythm of movements. Deceptive postures could be adapted to further affect predictability, however, that was deemed beyond the scope of this study. (cf., deception Brault et al., 2012)

### 3.1.3 Aims and hypotheses

In the current study it was aimed to further examine how various local and global sources of motion information affect coordination. In Chapter 2 it was found that in comparison to a combination of global and local information, expansion-compression information in isolation allowed for comparable movement in terms of spatial accuracy. Additionally, an interaction between condition and movement direction showed that the sphere condition was coordinated with more consistently when the leader was approaching. On one end of the spectrum, segmental information is hypothesized to improve the temporal synchrony, resulting in lower response times ($RT$) and a smaller lag in the follower’s movements (less negative $\varphi$). (Dugan & Bhat, 2005; Sartori et al., 2011) On the other hand, global information is hypothesized to increase the spatial accuracy, decreasing the deviation from the initial distance (less negative $\delta$) and increasing the optical size change (less positive $\alpha$). Cadence information is expected to lie in between the two ends of the spectrum and provide some of the benefits of local and global motion information. The manipulation of the viewpoint should show that facing the leader’s back increases the temporal synchronization and the spatial accuracy. However, if it is predominantly local information that caused the condition-direction interaction in Chapter 2, then this effect will only be shown in the conditions with local motion information. This would fuel the discussion that backward walking is not simply a reversed version of forward walking, despite current claims (Grasso et al., 1998; van Deursen, Flynn, McCrory, & Morag, 1998; Winter, Pluck, & Yang, 1989). Finally, it is expected that both the temporal and spatial accuracy will be less accurate when the leader is less regular (for clarity purposes labelled as ‘irregular’ in this study). It is furthermore expected that followers become more reliant on the more honest global information, when the leader’s movements are irregular (cf., deception, cf., Brault et al., 2012).
3.2 Methods

3.2.1 Participants

Nineteen male participants volunteered for the experiment (aged 21–42). Participants had normal, or corrected-to-normal, vision. Only participants with no known motor impairments that would limit the ability to walk and change direction were included. All participants were reasonably active and in good health. Participants were screened for experience in dance, fencing, boxing and martial arts, as coordinative skills acquired in such activities may influence distance keeping. No participants reported competitive experience in any of these activities. Thus, no further analysis was undertaken based on preferred sport information. One participant was excluded after partially completing the experiment. This participant could not complete the task due to an unrelated psychological disorder. His data was deemed unreliable and thus excluded (leaving 18 remaining participants). A confederate with similar characteristics to the other participants acted as the leader ‘participant’. In Table 3.1, the characteristics of the participants are shown.

Table 3.1: Descriptive characteristics (mean ± SD) of participants and leader.

<table>
<thead>
<tr>
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<th>Participants (n = 18)</th>
<th>Leader (n = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>28 ± 5.4</td>
<td>31</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>84 ± 8.2</td>
<td>69</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>183 ± 6.4</td>
<td>173</td>
</tr>
<tr>
<td>Exercise (hrs/week)</td>
<td>6 ± 3.2</td>
<td>10</td>
</tr>
<tr>
<td>Self-rated level of fitness (1 low – 10 high)</td>
<td>7 ± 0.8</td>
<td>7</td>
</tr>
</tbody>
</table>

3.2.2 Leader recording

By necessity, the leader’s movements were recorded (using Vicon Motion Systems, Inc., Centennial, CO) in advance of the follower participants’ data collection. A naïve ‘confederate’ was instructed to walk backwards and forwards. Contextual background information (i.e., textured floors, wall markings, etc.) was occluded to limit the influence of surrounding surfaces upon the leader’s movements. The timing of the turnaround points was indicated by a pre-set audio signal to control the regularity of the leader’s turnaround points. The timing at which the leader had to change direction was based on a near-random
distribution with known characteristics. Either the distribution was set to be ‘regular’ or ‘irregular’, with $2.22 \pm 0.67$ s (mean ± SD) or $1.90 \pm 0.94$ s (mean ± SD) between audio cues respectively. Before the patterns of the audio signals were finalized, the movements of the confederate were simulated using typical back-and-forth velocities in order to constrain the movements within the measurement volume. Of every set of near-random interval lengths that fit after the simulation, three different combinations were used to create an audio signal with the same level of regularity (in terms of time intervals between turnaround points). The actual regularity – or variability – as adopted by the leader participant is described using the average (± SD) of the standard deviation of the time intervals within each trial (see Table 3.2). A movement trial would last 25 seconds, as such, the within trial average of interval between turnaround points was $2.27 \pm 0.03$ s (mean ± SD) in the regular and $1.83 \pm 0.21$ s (mean ± SD) in the irregular trials. The various leader forms recordings were shown on a 25 Hz display and synchronized with the movement data (200 Hz) of the follower participants using an audio signal, thus securing a synchronization sensitivity of ±0.04 s.

Table 3.2: The levels of regularity of the leader signals described using the variability of the time intervals between turnaround points.

<table>
<thead>
<tr>
<th>Regularity level</th>
<th>Within trial turnaround points (number)</th>
<th>Time intervals within trial SD (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>12-13</td>
<td>$0.12 \pm 0.15$</td>
</tr>
<tr>
<td>Irregular</td>
<td>13-17</td>
<td>$0.70 \pm 0.12$</td>
</tr>
</tbody>
</table>

3.2.3 Animations

In Figure 3.1 an illustration is presented of the proposed spectrum, organized from local to global motion information. In the current study, the role of each type of information was examined by looking at the movement responses of participants following manipulated leader forms (see Figure 3.1) whilst additionally manipulating key task constraints (see Section 3.1.2). All aspects of the spectrum that were considered for this study were jointly available in the reference (avatar) condition. The ‘leader’ presented in this condition was a fully animated avatar with 15 moving segments. A virtual leader rather than a real person was used to accurately control and match the other conditions with the reference condition.
Follow the leader

Figure 3.1: Leader forms (as per Table 3.1) as presented to the follower participants; the arrows indicate the cadence movement of the static displays. From left to right: point-light, avatar, cadence XY, cadence Y, cadence X, fixed, cylinder and sphere.

In total, eight different leader forms were presented to the followers (Figure 3.1). A point-light condition was included to highlight the segmental motion information\(^7\). The avatar condition was included as a reference condition. Three cadence conditions were included showing the lateral and vertical cadence-related movements (see variations of ‘cadence’ in Figure 3.1) using the same shape as the avatar, but without moving segments (i.e., limbs did not move). The leader form would ‘sway’ laterally (cadence X), ‘bounce’ vertically (cadence Y) or ‘bounce and sway’ (cadence XY). These movements were directly derived from the leader’s movements at the c7 marker. The axis along which movement is incorporated is indicated by the suffix, X referring to the lateral and Y referring to the vertical axis. Lastly, to thoroughly examine the role of global motion information three ‘static’ conditions were included that do not display any segmental motion or cadence information. Note that the label static is used to dissociate between the segmental and cadence conditions, not to indicate the complete lack of movement. The first static condition is a ‘fixed’ avatar that moved back-and-forth (like a mannequin on a rail). It provided neither segmental nor cadence-related motion characteristics (‘fixed’, Figure 3.1). The followers were thus forced to rely on expansion-compression information alone. A second static condition was included in the form of a cylinder. This leader form had the same size as the fixed condition, but was more abstract and

\(^7\) Experimentally it would be appropriate to have a condition without expansion. After piloting this, however, it was decided that a PLD without expansion should not be incorporated. First of all, during the pilot testing it was found that participants found such leader videos too confusing and secondly, defining a form of spatial accuracy would be arbitrary as there would be no distance covered (and thus participants could not comply with the instruction ‘keeping the distance’).
did not show which direction the leader was facing. Lastly, a sphere condition was included, projected with a diameter equal to the height of the leader. A sphere expands and retracts more uniformly than a cylinder, and is therefore presumed to have an even stronger emphasis on expansion-compression information. All the conditions were presented in a randomized order and an overview of the types of available information is presented in Table 3.3.

Table 3.3: Information characteristics of presented leader forms. Double ticks indicate a presumed emphasis of that type of information.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Limb movement</th>
<th>Vertical sway</th>
<th>Lateral sway</th>
<th>Expansion-compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point-light</td>
<td>✔ ✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Avatar</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Cadence XY¹</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔</td>
</tr>
<tr>
<td>Cadence Y¹</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔</td>
</tr>
<tr>
<td>Cadence X¹</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔</td>
</tr>
<tr>
<td>Fixed¹</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td></td>
</tr>
<tr>
<td>Cylinder¹</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td></td>
</tr>
<tr>
<td>Sphere¹</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td></td>
</tr>
</tbody>
</table>

¹Movement based on the c7 marker of the leader

In contrast to Chapter 2, potential reference points (e.g., grid floor) were not present in the virtual display. The perceived displacement can therefore only be attributed to some movement characteristics of the leader, and not simply its displacement in relation to background information. In a normal camera image, the movement flows out of the centre of the image; however, the optic flow of an observer flows from eye height. Therefore, videos were generated using an artificial focal point, or centre of optical flow, to be projected at eye height. For practical reasons, the focal point was fixed at 1.80 m, although not every participant had the same height. Subsequently, the head of the leader would always be at the same height and the leader’s head was the centre of expansion-compression.

All trials were animated with camera perspectives either face-to-face (viewpoint F2F) with the leader or facing the back of the leader (viewpoint F2B) using Autodesk’s motion builder (Autodesk Inc., San Rafael, CA, 2013). Note that viewpoint does not have any effect on the visual appearance of the cylinder, nor the sphere. For these conditions, only the acceleration.
pattern will change with viewpoint. As has been shown by Ducourant et al. (2005) for example, preferred or intrinsic velocity when walking forwards is higher than when walking backwards. As such, the two viewpoints were compared to contrast the effect of movement and walking direction.

3.2.4 Measurement volume

The on-screen size of the projected leader form ranged from 0.74 m (far away) to 1.77 m (close by). If the follower would successfully maintain the virtual distance (i.e., nulled visual angle), this size range would translate to a maximal (virtual) displacement of 4.24 m. Taking the starting positions as displayed in Figure 3.2 into account, the participants would roughly move between C and E. Although in Chapter 2 it was found that participants consistently undershoot the leader’s displacement, the calibrated measurement volume was extended from B to F covering a total of 6 m. At 0.2 m from position B, A represents the screen on which the video is projected. Participants walked over a non-slip mat, with an even surface without recognition points on which the participants could anchor their movements. Embedded in the mat there were three small LEDs that indicated the participant’s starting position for that specific trial (feedback from participants after testing confirmed the LEDs were not visible when switched off). By including multiple starting positions, any effect of the starting position on the visual angle would be controlled for, as starting distance has previously been shown to influence follow-the-leader coordination (Ducourant et al., 2005).
3.2.5 Procedure

Participants were informed about the follow-the-leader task before signing informed consent. The follower was instructed to maintain the initial (virtual) distance as a life-size projection of the leader would move backwards and forwards. No specific instruction was given about how the participants had to follow the leader. Participants were not explicitly instructed about copying or imitating movements. It was only emphasized to maintain the distance as perceived from the start. Each trial started with a three-second audio tone. At the same time, an LED would alight to indicate the participant’s starting position. The participant then positioned himself next to the LED and held up his arms in a T-pose (for data processing purposes). When the audio cue stopped, participants could lower their arms and after another two seconds, the leader form would appear on the projection screen, after which the trial began immediately. The leader’s movements would last for 25 seconds, after which there was an eight second break. After every six trials, a 30-second break was scheduled, during which the participant was asked to indicate the perceived difficulty of the preceding trial. Ethical approval was obtained from the human ethics committee of the University of Otago prior to data collection.
3.2.6 Outcome measures

As with Chapter 2, the anterior-posterior whole-body displacements, based on the head markers, were subjected to a piecewise cubic spline interpolation to fill any gaps, after which the data was filtered using a second order low-pass Butterworth filter with a cut-off frequency of 5 Hz. The movement characteristics (i.e., velocity and number of steps) of both the follower and leader were computed first. Velocity ($v$) was calculated for each direction separately, in other words velocity was always positive. The same measures to quantify the temporal synchrony, the point-estimate relative phase ($\varphi$) and response times ($RT$), were included as in Chapter 2. Note that negative $\varphi$ values indicate that the phasing of the leader was ahead of the phasing of the follower. Also for the spatial accuracy, the same measure, rate of change of visual angle velocity ($\dot{\alpha}$), was included. In order to more accurately test the follower’s task-goal – maintain the initial distance – the current study extended the analysis of the spatial accuracy by computing the ‘virtual distance’ over time (see Section 3.2.6.1 for a detailed explanation). A negative relative distance indicates that the virtual distance between the follower and leader has decreased. Negative values of $\dot{\alpha}$ indicate that the visual angle was decreasing, which corresponds with an increasing – but not necessarily positive – virtual distance ($\delta$). In terms of $\dot{\alpha}$ and $\delta$, the instruction ‘maintaining distance’ can be quantified as a target of 0 deg·s$^{-1}$ or 0 m, respectively. For $\varphi$ and $RT$, the implied target is 0 rad and 0 ms respectively. The time-series variables ($\delta$, $\dot{\alpha}$ and $\varphi$) were again assessed in detail using the error measures as set out in Section 2.2.6.3. Put simply, the constant deviation ($CD$) can be considered as the lead-lag relationship, the variable error ($VE$) as the consistency, and absolute deviation ($AD$) as the accuracy of the outcome measure it relates to.

The effect of the leader’s movement direction (i.e., approaching or receding) was analysed for the measures for spatial accuracy and $RT$. Direction was based on the leader’s turnaround points and labelled as ‘approaching’ or ‘receding’, therefore irrespective of viewpoint. For $RT$, ‘approaching’ referred to the response time after the leader was approaching and initiated a receding movement. Note that the direction effect could not be tested for the discrete relative phase ($\varphi$), as each within-trial value for $\varphi$ includes the phase lags of the movement cycle based on approaching-receding-approaching or receding-approaching-receding turnaround points (see 2.2.6.2). Nevertheless, the discrete relative phase was more appropriate than a continuous relative phase which would be unable to cope with variations in phasing between follower and leader (e.g., missed turnaround points).
3.2.6.1 Virtual distance ($\delta$)

Spatial accuracy can be defined as the deviation from the initial distance between follower and leader over time. However, as the virtual leader did not actually physically change distance – the projection screen was stationary – there is no physical distance that can be measured. Instead, a virtual distance can be calculated using the known projection size of the leader. To clarify, Figure 3.3 provides a schematic overview of how $\delta$ is determined. The horizontal axis represents the movement axis with the projection screen at 0 m. In the top panel the first part of Equation 3.1 visualized. Based on that ratio a ‘perfect follower’ (in terms of keeping $\alpha$ constant) can be estimated. The bottom panel shows what $\delta$ may look like if a follower would cover less distance than anticipated by the optical size change of the leader object. Given that the optical size of the leader is correlated with its virtual displacement, the following ratio is known:

$$\frac{x_F(0)}{a(0)} = \frac{x_{vl}(t)}{a(t)}$$ \hspace{1cm} \text{Equation 3.1}

Where $x_F(0)$ is the follower’s distance to the screen at the start of the trial, $a(0)$ is the projection vertical size at the start of the trial, $a(t)$ the projection size at a given time point $t$ and $x_{vl}(t)$ is the virtual position of the leader at a given time point $t$. Finally, $x_{vl}(t)$ can be used to determine the $\delta(t)$:

$$\delta(t) = x_F(t) - x_{vl}(t)$$ \hspace{1cm} \text{Equation 3.2}

For $\delta$ (in m), positive values indicate that the follower is getting further away from the leader than it was initially. $\delta$ is the closest approximation of interpersonal distance (relating the avatar to a real physical person) available in this experiment. All kinematic analyses were performed using MATLAB R2011a (The MathWorks Inc., Natick, MA, 2011).
3.2.7 Statistical analysis

There were eight different leader conditions and each participant performed 12 trials in each condition\(^8\) (1,728 trials in total). Using R (R Core Team, 2013), a linear mixed effects models analysis (LMM) (Zuur, Ieno, Walker, Salveliev, & Smith, 2009) was used to test the effect of the primary factor (condition). Additional constraints (viewpoint, regularity, and direction) were included in the model to control for variability and thus increase the precision of estimates for condition. Note that direction could not be included for \(\varphi\) (see Section 3.2.6).

\(^{8}\) Rio et al. (2014) used eight trials per condition for their study on visual control in a following task in a virtual environment. Power calculations based on their data (difference in speed; \(\omega^2 = 0.690\), nine groups, eight repetitions per trial, 12 participants) show that a sample size of 16 has a power of 0.8.
The dataset was treated as a repeated measures dataset (Goldstein, Healy, & Rasbash, 1994). Using linear mixed models for a repeated measures design allowed for random intercepts in the regression models, which meant that both inter-individual variation and within individual correlation could be accounted for. A standardized iterative protocol was used to find the best fitting model. First, a range of models were fitted to determine the best variance structure. One of the candidate models also allowed for unstructured covariance across the repeated observations. If necessary, a component was included in the regression model to adopt the best variance structure. Then, the fixed effects model was run to establish which components had to be included in the model. The model was selected based on which fixed effects had a significant effect, determined by the lowest AIC (Akaike's information criterion, Akaike, 1974). To allow for random effects, and thus have a within subjects repeated measures structure, participant was included as a component by default. Levene’s tests were applied to the final model to see if the component variance was significantly different ($p < 0.05$). If the variance was unequal, the process was repeated with an additional component in the regression model to further adjust the variance structure. Normality was checked, but even the variables that were not strictly normally distributed could be included in the model without correction, given the large number of data entries (cf., central limit theorem; cf., Lumley, Diehr, Emerson, & Chen, 2002). Although the procedure was standardized, the process of selecting the best model was still partly subjective. Finally, the main and interaction effects could be established based on the final model, once the requirements were satisfied. Results were summarized using least-square means (LSmeans, Searle, Speed, & Milliken) and the corresponding standard errors (SE). Post-hoc contrasts were tested for significance using Tukey HSD tests.

### 3.3 Results

This section is divided into two parts. In the first part, the main effects of the constraints (viewpoint, regularity and direction) are presented. This will help explain how the nature of the task influenced follow-the-leader coordination, and will subsequently allow for a better understanding of the condition effects. The main and interaction effects with condition are explained in the second part. Here, the influence of the different leader forms (condition) on follow-the-leader coordination is explored.
Participants experienced the task as moderately easy, scoring the task difficulty as $33 \pm 22\%$ (mean $\pm$ SD). Difficulty was indicated on a slider bar, of which the marked position was converted to a percentage based on the total length of the slider (0% being easy and 100% difficult). The participants’ perceived difficulty was not systematically affected by condition or viewpoint.

3.3.1 Part 1 – Task constraints

3.3.1.1 Viewpoint

Viewpoint had a significant effect on the follower-leader coordination for most variables (see Table 3.4). Most notably, followers were better synchronized in time with the leader and followed spatially more accurate, when the follower faced the back of the leader (F2B) than vice versa. This was also reflected in lower error measures ($VE$ and $AD$), indicating a more stable and accurate synchrony. In both viewpoints, $CD \varphi$ was negative, indicating that the leader led the followers. Given that $CD \varphi$ was significantly closer to the target (0 rad) in viewpoint F2B, the temporal synchrony was found to be better in viewpoint F2B. This effect was corroborated with a lower $RT$. The temporal synchrony appeared to be only subtly affected by viewpoint, whereas the differences in spatial accuracy appeared more substantial. However, as will be explained in Part 2 of the results section, this was partially due to interaction effects with condition.
Table 3.4: Mean (± SE) of viewpoints face-to-face (F2F) and face-to-back (F2B) on all outcome variables. For the individual measures the leader (L) and follower (F) are displayed separately. Note that movement characteristics of the leader (Steps and v) are only displayed as reference since F2F and F2B were generated from the same movement trajectories.

<table>
<thead>
<tr>
<th></th>
<th>F2F</th>
<th>F2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steps (number)</td>
<td>L 43.04 ± 0.35</td>
<td>F 38.39 ± 1.41</td>
</tr>
<tr>
<td></td>
<td>F 38.62 ± 1.41</td>
<td></td>
</tr>
<tr>
<td>v (m·s⁻¹)</td>
<td>L 0.65 ± 0.00</td>
<td>F 0.60 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>F 0.59 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>Temporal synchrony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT (ms)</td>
<td>***113.17 ± 2.81</td>
<td>110.72 ± 2.81</td>
</tr>
<tr>
<td>φ (rad)</td>
<td>CD**-0.91 ± 0.02</td>
<td>-0.89 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>VE**0.34 ± 0.01</td>
<td>0.31 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>AD**0.85 ± 0.02</td>
<td>0.83 ± 0.02</td>
</tr>
<tr>
<td>Spatial accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>δ (m)</td>
<td>CD***-0.13 ± 0.14</td>
<td>0.02 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>VE***1.11 ± 0.04</td>
<td>0.91 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>AD***1.25 ± 0.04</td>
<td>1.09 ± 0.04</td>
</tr>
<tr>
<td>˙α (deg·s⁻¹)</td>
<td>CD***0.15 ± 0.02</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>VE***2.33 ± 0.13</td>
<td>2.28 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>AD***2.13 ± 0.10</td>
<td>1.96 ± 0.10</td>
</tr>
</tbody>
</table>

Significant main effects of viewpoint are indicated using * (p < 0.05), ** (p < 0.01) and *** (p < 0.001)

3.3.1.2 Regularity

The regular trials were more successfully followed than the irregular trials, as evidenced by an improved temporal synchrony (see Table 3.5). The temporal synchronization (RT and CD φ) was better in the regular compared to the irregular trials. The lead-lag relationship was also more stable and accurate (lower VE and AD φ) in the regular trials. The spatial accuracy (CD δ and CD ˙α) shows the opposite effect of the temporal synchronization: the leader was more accurately followed in the irregular compared to regular trials. That is, the overall (i.e., across both directions) average relative distance between follower and leader was closer to 0 m in the irregular trials. However, the error measures indicated that the spatial accuracy is more stable and accurate (VE and AD of both ˙α and δ) in the regular trials compared to the irregular trials. Furthermore, note that the follower’s velocity was lower in the irregular trials compared to the regular trials.
Table 3.5: Mean (± SE) of regularity on all outcome variables. For the individual measures the leader (L) and follower (F) are displayed separately.

<table>
<thead>
<tr>
<th></th>
<th>Regular</th>
<th>Irregular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steps (number)</td>
<td>L 41.82 ± 0.37</td>
<td>44.25 ± 0.40</td>
</tr>
<tr>
<td></td>
<td>F 38.93 ± 1.41</td>
<td>38.08 ± 1.42</td>
</tr>
<tr>
<td>v (m·s⁻¹)</td>
<td>L 0.67 ± 0.00</td>
<td>0.64 ± 0.00</td>
</tr>
<tr>
<td></td>
<td>F 0.61 ± 0.02</td>
<td>0.57 ± 0.02</td>
</tr>
</tbody>
</table>

**Temporal synchrony**

<table>
<thead>
<tr>
<th></th>
<th>Regular</th>
<th>Irregular</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT (ms)</td>
<td>109 ± 3</td>
<td>115 ± 3</td>
</tr>
<tr>
<td>φ (rad)</td>
<td>CD -0.75 ± 0.02</td>
<td>-1.05 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>VE 0.27 ± 0.01</td>
<td>0.38 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>AD 0.74 ± 0.02</td>
<td>0.94 ± 0.02</td>
</tr>
</tbody>
</table>

**Spatial accuracy**

<table>
<thead>
<tr>
<th></th>
<th>Regular</th>
<th>Irregular</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ (m)</td>
<td>CD -0.11 ± 0.14</td>
<td>0.00 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>VE 0.98 ± 0.04</td>
<td>1.04 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>AD 1.13 ± 0.04</td>
<td>1.21 ± 0.04</td>
</tr>
<tr>
<td>ā (deg·s⁻¹)</td>
<td>CD 0.11 ± 0.02</td>
<td>0.07 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>VE 2.17 ± 0.13</td>
<td>2.44 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>AD 1.84 ± 0.10</td>
<td>2.24 ± 0.10</td>
</tr>
</tbody>
</table>

Significant main effects of regularity are indicated using * (p < 0.05), ** (p < 0.01) and *** (p < 0.001)

3.3.1.3 Direction

It was found that the followers performed most consistently (decreased VE φ, VE δ and VE ā) when the leader was approaching; however, this was also correlated with a larger virtual distance between follower and leader (see Table 3.6). When the leader advanced, CD δ decreased and CD ā increased, and vice versa when the leader receded. This indicates that followers undershoot the virtual displacement of the leader in both directions. The undershoot was larger when the leader was approaching. Despite the increased undershoot, the stability and accuracy of the spatial accuracy (VE and AD of both ā and δ) increased when the leader was approaching. When the leader was approaching v was higher compared to when the leader was receding. In addition to the main effects of direction, there are some important interactions with direction that will be explained further in the next section.
Table 3.6: Mean (± SE) of direction for all outcome variables. For the individual measures the leader (L) and follower (F) are displayed separately. Note that movement characteristics of the leader (Steps and v) are only displayed as reference since Approaching and Receding were generated from the same movement trajectories.

<table>
<thead>
<tr>
<th></th>
<th>Approaching</th>
<th>Receding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steps (number)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>21.52 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>19.32 ± 0.70</td>
<td>19.19 ± 0.70</td>
</tr>
<tr>
<td>v (m·s⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>0.65 ± 0.00</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.61 ± 0.02</td>
<td>0.57 ± 0.02</td>
</tr>
<tr>
<td><strong>Temporal synchrony</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT (ms)***</td>
<td>108 ± 3</td>
<td>116 ± 3</td>
</tr>
<tr>
<td><strong>Spatial accuracy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>δ (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>0.44 ± 0.14</td>
<td>0.33 ± 0.14</td>
</tr>
<tr>
<td>F</td>
<td>0.94 ± 0.04</td>
<td>1.09 ± 0.04</td>
</tr>
<tr>
<td>VE***,+++</td>
<td>1.13 ± 0.04</td>
<td>1.20 ± 0.04</td>
</tr>
<tr>
<td>α (deg·s⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>1.05 ± 0.02</td>
<td>-0.87 ± 0.03</td>
</tr>
<tr>
<td>F</td>
<td>2.24 ± 0.13</td>
<td>2.37 ± 0.13</td>
</tr>
<tr>
<td>VE***,+++</td>
<td>2.00 ± 0.10</td>
<td>2.09 ± 0.10</td>
</tr>
<tr>
<td>AD***,+++</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Significant main effects of direction are indicated using * (p < 0.05), ** (p < 0.01) and *** (p < 0.001).

Significant viewpoint-direction interactions are indicated using * (p < 0.05), ** (p < 0.01) and *** (p < 0.001).

### 3.3.1.4 Viewpoint-direction interaction

An effect of direction has different implications when there also is an interaction with viewpoint. As indicated in Table 3.6, there were significant viewpoint-direction interactions for VE δ, CD α, VE α and AD α. Overall, participants performed better with viewpoint F2B (i.e., CD closer to target, lower VE and AD) than with viewpoint F2F (see Table 3.4), and an approaching leader was somewhat performed better with than a receding leader (see Table 3.6). Compared to a receding leader, VE δ decreased significantly when the leader was approaching both when the leader was presented in viewpoint F2F (ΔVE δ = 0.20 m, t(3024) = 13.224, p < 0.001) and F2B (ΔVE δ = 0.07 m, t(3024) = 8.845, p < 0.001), see Figure 3.4 (top panel). Furthermore, the difference between an approaching and receding leader was significantly larger in viewpoint F2F (ΔVE δ = 0.18 m, t(3027) = 10.062, p < 0.001). Furthermore, for AD α the contrasts only revealed a significant difference for direction when the leader was presented in viewpoint F2F (t(3027) = 4.4704, p < 0.001). In fact, contrasts...
Follow the leader
revealed that compared to a receding leader $VE \dot{\alpha}$ was significantly higher (i.e., less stable, $\Delta VE \dot{\alpha} = 0.07$ rad, $t(3024) = 2.904, p = 0.019$) when the leader was approaching for a leader presented in viewpoint F2B (see Figure 3.4, bottom panel). Note that for $CD \dot{\alpha}$ and $VE \dot{\alpha}$ also significant viewpoint-direction-condition interactions were found.

Figure 3.4: Overview of the significant viewpoint-direction interactions for $VE \delta$ (top) and $AD \dot{\alpha}$ (bottom). Significant differences for direction are indicated for F2F (*) and F2B (+) separately. Significantly different slopes are indicated with $\Delta$. 
Table 3.7: Means (± SE) of each condition are displayed for all outcome variables. Note that interactions might influence the appearance of the condition effect as perceived from the table.

<table>
<thead>
<tr>
<th></th>
<th>Point-light</th>
<th>Avatar</th>
<th>Cadence XY</th>
<th>Cadence Y</th>
<th>Cadence X</th>
<th>Fixed</th>
<th>Cylinder</th>
<th>Sphere</th>
</tr>
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<tbody>
<tr>
<td>Steps</td>
<td>L</td>
<td>43.04 ± 0.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F^1</td>
<td>40.17 ± 1.45</td>
<td>39.87 ± 1.48</td>
<td>38.60 ± 1.45</td>
<td>38.05 ± 1.45</td>
<td>38.11 ± 1.47</td>
<td>38.1 ± 1.46</td>
<td>37.9 ± 1.44</td>
</tr>
<tr>
<td>v (m·s^{-1})</td>
<td>L</td>
<td>0.66 ± 0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F^{1,2,3}</td>
<td>0.61 ± 0.02</td>
<td>0.62 ± 0.02</td>
<td>0.58 ± 0.02</td>
<td>0.58 ± 0.02</td>
<td>0.59 ± 0.02</td>
<td>0.59 ± 0.02</td>
<td>0.6 ± 0.02</td>
</tr>
<tr>
<td>Temporal synchrony</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT (ms)^{1,2,3}</td>
<td></td>
<td>104 ± 3</td>
<td>99 ± 3</td>
<td>118 ± 3</td>
<td>114 ± 3</td>
<td>119 ± 3</td>
<td>112 ± 3</td>
<td>117 ± 3</td>
</tr>
<tr>
<td>φ (rad)</td>
<td>CD^{1}</td>
<td>-0.87 ± 0.02</td>
<td>-0.8 ± 0.02</td>
<td>-0.94 ± 0.03</td>
<td>-0.92 ± 0.02</td>
<td>-0.95 ± 0.02</td>
<td>-0.92 ± 0.02</td>
<td>-0.93 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>VE</td>
<td>0.33 ± 0.01</td>
<td>0.32 ± 0.01</td>
<td>0.33 ± 0.01</td>
<td>0.34 ± 0.01</td>
<td>0.33 ± 0.01</td>
<td>0.32 ± 0.01</td>
<td>0.32 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>AD^{1,2,3}</td>
<td>0.79 ± 0.02</td>
<td>0.75 ± 0.02</td>
<td>0.86 ± 0.02</td>
<td>0.85 ± 0.02</td>
<td>0.89 ± 0.02</td>
<td>0.85 ± 0.02</td>
<td>0.88 ± 0.02</td>
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<tr>
<td>Spatial accuracy</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>δ (m)</td>
<td>CD^{1,2}</td>
<td>-0.21 ± 0.14</td>
<td>0.12 ± 0.14</td>
<td>0.03 ± 0.14</td>
<td>-0.14 ± 0.14</td>
<td>-0.11 ± 0.14</td>
<td>-0.03 ± 0.14</td>
<td>0.01 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>VE^{1,2}</td>
<td>1.00 ± 0.04</td>
<td>1.02 ± 0.04</td>
<td>1.02 ± 0.04</td>
<td>0.99 ± 0.04</td>
<td>1.00 ± 0.04</td>
<td>1.03 ± 0.04</td>
<td>1.07 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>AD^{1,2}</td>
<td>1.15 ± 0.05</td>
<td>1.16 ± 0.05</td>
<td>1.16 ± 0.05</td>
<td>1.11 ± 0.05</td>
<td>1.18 ± 0.05</td>
<td>1.19 ± 0.05</td>
<td>1.22 ± 0.05</td>
</tr>
<tr>
<td>ȧ (deg·s^{-1})</td>
<td>CD^{4}</td>
<td>0.09 ± 0.03</td>
<td>0.09 ± 0.04</td>
<td>0.08 ± 0.03</td>
<td>0.03 ± 0.03</td>
<td>0.10 ± 0.03</td>
<td>0.09 ± 0.03</td>
<td>0.11 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>VE^{1,2,3,4}</td>
<td>2.40 ± 0.14</td>
<td>2.13 ± 0.14</td>
<td>2.28 ± 0.14</td>
<td>2.26 ± 0.14</td>
<td>2.39 ± 0.14</td>
<td>2.33 ± 0.14</td>
<td>2.37 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>AD^{1,2,3}</td>
<td>2.07 ± 0.10</td>
<td>1.85 ± 0.10</td>
<td>2.05 ± 0.10</td>
<td>2.02 ± 0.10</td>
<td>2.16 ± 0.10</td>
<td>2.06 ± 0.10</td>
<td>2.09 ± 0.10</td>
</tr>
</tbody>
</table>

Significant effects (p < 0.05) found for: ¹ condition, ² condition-viewpoint, ³ condition-regularity, ⁴ condition-direction
3.3.2 Part 2 – Effect of leader information

In Table 3.7, the main effects of condition are summarized for all outcome measures. Below, an overview is presented of the main and interaction effects for each outcome variable. Specific comparisons are given if they stand out from the other comparisons using post-hoc contrasts. The condition interactions are explored in more detail using the difference scores of any interacting constraints (indicated with Δ).

3.3.2.1 Movement characteristics

The number of steps and velocity inform about how the movements of the follower were regulated at the specific level of the gait characteristics. Participants adopted rather similar movement characteristics for the point-light and the avatar conditions. For the cadence and static conditions however, it appeared that the followers took less steps and moved slower. Additionally, it was shown that the velocity of the followers in the cylinder and sphere conditions was not affected by regularity. For the number of steps (see Table 3.7) no interaction effects were found, but there was a significant main effect of condition ($F(7,3003) = 12.210$, $p < 0.001$). Contrasts revealed that the point-light and avatar condition were not significantly different from each other, but participants took significantly more steps in both the point-light and avatar condition compared to all cadence and static conditions. The main effect for $v$ was found to be significant ($F(7,3033) = 18.968$, $p < 0.001$). Overall, $v$ was the highest in the avatar condition, closely followed by the point-light condition (see Table 3.7). Participants moved significantly faster in the avatar condition compared to all other conditions, except the point-light condition as revealed by the post-hoc contrasts. A significant condition-regularity interaction was found for $v$ ($F(7,3033) = 3.133$, $p = 0.003$). Although for most conditions the regular trials were performed consistently faster, contrasts of the condition-regularity interaction revealed that for both the cylinder and the sphere conditions the difference between regular and irregular leader was not significant. Although it was not examined statistically (as the conditions were generated from the same leader movement trajectories), followers seemed to take fewer Steps than the leader (mean ± SE = 43.04 ± 0.35) and followers appeared to move slower than the leader (mean ± SE = 0.66 ± 0.01 m·s$^{-1}$). This would suggest that followers adopted a secure and reactive strategy.
3.3.2.2 Temporal synchrony

For both $RT$ and $\phi$ it was evident that the leader forms containing segmental motion information (point-light and avatar condition) resulted in a tighter temporal synchrony than both the cadence and static conditions. A significant main effect of condition was found for $RT$ (see Table 3.7), $F(7,1501) = 41.127, p < 0.001$. Post-hoc contrasts revealed that $RT$ was significantly lower in the avatar condition compared to all other conditions. In the point-light condition, $RT$ was also significantly smaller than all cadence and all static conditions (see Figure 3.5). Furthermore, a significant condition-regularity interaction was found for $RT$ ($F(7,3017) = 4.456, p < 0.001$), see Figure 3.5. Post-hoc contrasts showed that $RT$ in the irregular trials was significantly larger for all cadence and static conditions compared to regular trials, except for cadence X. For the point-light and avatar conditions the difference between the regular and irregular trials was not significant. Lastly, a significant condition-viewpoint interaction was found for $RT$ ($F(7,3017) = 5.347, p < 0.001$). Only in the fixed condition $RT$ decreased significantly when the leader was presented in viewpoint F2B compared to F2F ($\Delta RT = 7.98 \text{ ms}, t(3017) = 3.642, p = 0.025$). Overall this suggests neither cadence nor expansion-compression information in isolation provided the same advantage for $RT$ that segmental motion information does.

![Figure 3.5: The significant condition-regularity interaction for RT (mean and SE). The major significant post-hoc differences of the main effect for condition are indicated with ∆; the conditions that are significantly affected by regularity are indicated with *.

Across all conditions, the leader was on average indeed leading the follower (as revealed by a negative $CD \phi$), although within-trial fluctuations occurred (as indicated by the larger $AD \phi$ compared to $VE \phi$). For $CD \phi$ a main effect of condition was present ($F(7,1515) = 26.944, p < 0.001$), but no further interaction effects were found (see Table 3.7). $CD \phi$ was significantly
closer to the target (0 rad) in the avatar condition compared to all other conditions. Then the point-light condition was significantly closer to the target compared to most other (i.e., not the avatar) conditions. Only the difference between the point-light and sphere condition was not significant. For $VE \varphi$, no significant main or interaction effects were found of condition. A significant main effect for condition was revealed for $AD \varphi$ ($F(7,1501) = 32.718, p < 0.001$). Post-hoc contrasts revealed that the point-light and avatar condition, although not significantly different from each other, were significantly different from all cadence and static conditions (see Table 3.7). Additionally, a significant condition-regularity interaction was found ($F(7,1501) = 2.822, p = 0.006$). $AD \varphi$ was significantly smaller in the regular trials for all conditions. In Figure 3.6 it can be observed that in the irregular trials the point-light condition was not significantly different from the avatar condition, whereas in the regular trials $AD \varphi$ was significantly larger in the point-light compared to the avatar condition ($\Delta AD \varphi = 0.071$ rad, $t(3017) = 5.062, p < 0.001$). In fact, in the regular trials the point-light condition was not even significantly different from the cadence Y, fixed or sphere conditions. Additionally, a significant condition-viewpoint interaction was found for $AD \varphi$ ($F(7,1501) = 2.224, p = 0.030$). Only in the fixed condition $AD \varphi$ decreased significantly in viewpoint F2B compared to viewpoint F2F ($\Delta AD \varphi = 0.07$ rad, $t(1501) = 3.738, p = 0.018$). Interestingly, the difference between $AD \varphi$ and $VE \varphi$ was quite substantial (see Table 3.7), indicating that the lead-lag relationship was regularly reversed as well (i.e., the follower became ‘ahead of’ the leader).

Overall the $\varphi$ results showed that indeed segmental motion information provides a temporal advantage, similar to the $RT$ results. Additionally, it was shown that the segmental motion information in the point-light condition allows the participants to more efficiently cope with an irregular leader.
3.3.2.3 Spatial accuracy

The spatial accuracy was influenced by manipulations on either end of the continuum. The point-light condition was found to affect the spatial accuracy particularly when viewpoint was manipulated. It also was revealed that the isolation of global motion information facilitates the stability and accuracy of the spatial accuracy. Finally, there is evidence that the cadence Y condition provides extra information to cope with the manipulated task constraints. A main effect was found for condition on $CD$ (see Table 3.7): $F(7,3048) = 9.600, p < 0.001$. Post-hoc contrasts revealed that the avatar condition was significantly different from most other conditions. The cadence XY, fixed and cylinder condition were not significantly different from the avatar condition. However, these effects would have been influenced by a significant condition-viewpoint interaction ($F(7,3048) = 5.710, p < 0.001$). Post-hoc contrasts revealed that only for the cylinder ($\Delta CD = 0.26 \text{ m}, t(3048) = 3.792, p = 0.018$) and sphere ($\Delta CD = 0.42 \text{ m}, t(3048) = 5.938, p < 0.001$) the effect of viewpoint was significant. Furthermore, in the point-light condition, $\Delta CD$ was significantly lower compared to most conditions when the leader was presented in viewpoint F2B, whereas in viewpoint F2F none of these differences were significant (Figure 3.7, top panel). For $VE$ a main effect of condition was found (see v): $F(7,3047) = 6.560, p < 0.001$. The cylinder condition stood out as having a significantly larger $VE$ compared to all conditions, except the avatar and cadence XY conditions. The sphere condition on the other hand stood out as it had a significantly smaller $VE$ compared to the avatar, cadence XY, fixed and cylinder conditions. Although viewpoint F2F was performed with consistently less stable (i.e., higher $VE$), a condition-viewpoint interaction was also found ($F(7,3047) = 4.053, p < 0.001$). Post-hoc contrasts revealed that
\( \Delta VE \delta \) in the sphere condition was significantly lower compared to most conditions when the leader was presented in viewpoint F2F, whereas in viewpoint F2B none of these differences were significant (see Figure 3.7, bottom panel). The main effect for \( AD \delta \) (see Table 3.7) was significant (\( F(7,3047) = 2.531, p = 0.014 \)). Post-hoc contrasts only revealed that cadence Y was significantly smaller than the cylinder condition (\( \Delta AD \delta = 0.11 \text{ m}, t(3047) = 3.851, p = 0.003 \)). Furthermore, there was a condition-viewpoint interaction for \( AD \delta \) (\( F(7,3047) = 2.782, p = 0.007 \)). Interestingly, the viewpoint effect was not significant for the cadence Y and sphere conditions, but all other conditions had a significantly lower \( AD \delta \) when the leader was presented in viewpoint F2B.

![Figure 3.7](image)

Figure 3.7: The significant condition-viewpoint interactions for \( CD \delta \) (top) and \( VE \delta \) (bottom) are shown (mean and SE). The most prominent differences between conditions are indicated with \( \Delta \). The conditions that are significantly affected by viewpoint are indicated with *.

No main effect for condition was found for \( CD \dot{\alpha} \). This may be explained by a strong condition-direction interaction effect (\( F(7,3003) = 20.477, p < 0.001 \)), see Figure 3.8. Post-hoc contrasts revealed that the avatar and point-light conditions were in fact significantly closer to the target (0 deg·s\(^{-1}\)) compared to most conditions, that is more positive with a receding and more negative with an approaching leader. Only the difference with the fixed
and cylinder condition was not significant when the leader was receding. The main effect of condition on \(VE \dot{\alpha}\) was significant \((F(7,3024) = 14.949, p < 0.001)\). The avatar condition had a significantly lower \(VE \dot{\alpha}\) (i.e., more stable) compared to all other conditions. The point-light condition had a significantly higher \(VE \dot{\alpha}\) (i.e., less stable) compared to the avatar \((\Delta VE \dot{\alpha} = 0.27 \text{ deg} \cdot \text{s}^{-1}, t(3024) = 7.398, p < 0.001)\), cadence XY \((\Delta VE \dot{\alpha} = 0.12 \text{ deg} \cdot \text{s}^{-1}, t(3024) = 3.466, p = 0.013)\) and cadence Y \((\Delta VE \dot{\alpha} = 0.14 \text{ deg} \cdot \text{s}^{-1}, t(3024) = 3.955, p = 0.002)\) conditions (see Table 3.7). On top of the main effect, a condition-viewpoint effect was also found for \(VE \dot{\alpha}\) \((F(7,3024) = 5.971, p < 0.001)\). Although generally \(VE \dot{\alpha}\) was lower with viewpoint F2B, only for the cylinder this difference was found significant \((\Delta VE \dot{\alpha} = 0.17 \text{ deg} \cdot \text{s}^{-1}, t(3024) = 3.629, p = 0.026)\). Furthermore, a significant condition-regularity interaction was found \((F(7,3024) = 3.224, p = 0.002)\). Most conditions had a significantly lower \(VE \dot{\alpha}\) (i.e., more stable) with a regular leader. Only the avatar and cadence Y conditions were not affected significantly by regularity. Finally, the condition-direction interaction was also significant \((F(7,3024) = 2.061, p = 0.04)\). It revealed that although for all conditions an approaching leader resulted in a lower \(VE \dot{\alpha}\), this was only statistically significant for the cadence XY \((\Delta VE \dot{\alpha} = 0.20 \text{ deg} \cdot \text{s}^{-1}, t(3024) = 4.320, p = 0.002)\) and sphere conditions \((\Delta VE \dot{\alpha} = 0.22 \text{ deg} \cdot \text{s}^{-1}, t(3024) = 2.384, p < 0.001)\).

Post-hoc contrasts of the main effect of condition on \(AD \dot{\alpha}\) \((F(7,3027) = 22.5045, p < 0.001)\) revealed that \(AD \dot{\alpha}\) in the avatar condition was significantly smaller (i.e., more accurate) than all the other conditions (see Table 3.7). The cadence X condition was significantly the worst out of all condition (i.e., highest \(AD \dot{\alpha}\)). Additionally, the condition-viewpoint interaction was also significant \((F(7,3027) = 5.376, p = 0.003)\). Although for most conditions, \(AD \dot{\alpha}\) significantly decreased (i.e., more accurate) when the leader was presented in viewpoint F2B, this difference was not significant for the point-light and cadence Y conditions. Lastly, a significant condition-regularity interaction was found \((F(7,3027) = 3.926, p < 0.001)\). All conditions showed a significant increase in \(AD \dot{\alpha}\) in the irregular trials compared to the regular trials. The interaction may be explained by the difference between the cadence Y and X conditions. With an irregular leader, cadence Y was significantly more accurate (i.e., lower \(AD \dot{\alpha}\), \(t(3027) = 4.269, p = 0.002)\) compared to cadence X, whereas this difference between conditions was not significant with a regular leader.

In sum, viewpoint F2F was generally performed with worse (i.e., lower stability and accuracy of \(\dot{\alpha}\)) and the same applies to an irregular leader. Furthermore, the results for \(\dot{\alpha}\) suggest that the cadence Y condition stands out somewhat compared to the other cadence (and static)
conditions. Cadence Y was affected less by regularity on the stability and accuracy (i.e., $VE \dot{\alpha}$ and $AD \dot{\alpha}$) of the visual angle velocity.

![Figure 3.8: The significant condition-direction interactions for $CD \dot{\alpha}$. The main significant differences between condition are indicated for each direction separately ($\Delta$).](image)

### 3.4 Discussion

The current study aimed to examine the locomotion responses to a proposed spectrum of information in a follow-the-leader task. On one end of the spectrum leader forms were included that displayed predominantly local (i.e., segmental) motion information. On the other end leader forms displayed a high degree of global (i.e., expansion-compression) motion information. Additionally, key task constraints (i.e., viewpoint and regularity) were manipulated to further tease apart the influence of the different types of information on the followers’ locomotion responses. Results indicated that a variety of coordination strategies emerged as the task and the available information changed. It was notable that the constraints had a strong and consistent effect across conditions. Overall, it was clear that the availability of segmental motion information in the visual display enhanced temporal synchronization, but it did not enhance spatial accuracy to the same extent. Furthermore, although influenced by viewpoint, spatial accuracy was enhanced most when only global motion information was available. It may be that followers could only focus on the more honest visual angle information, resulting in more stable and accurate following. Information about walking cadence was not found to substantially influence coordination. Overall, it can be surmised that distance-keeping can be achieved with (a combination of) many different types of information. The task constraints strongly influence behaviour, but followers typically manage to flexibly negotiate the information available.
3.4.1 Global to local motion information

This study aimed to establish a spectrum of information used for follow-the-leader coordination. Although a range of ways to use different types of information is evident, the usefulness of each of these sources of information is not easily situated along a spectrum (at least, a linear spectrum as proposed in Figure 3.1). The cadence conditions were intended to sit between local and global motion information. However, given the similarity of the results across cadence and fixed conditions, it is assumed that the vertical and lateral sway signifying cadence information was not exploited for distance-keeping in the current task. Arguably, the unnatural appearance of isolated cadence information may have put followers off. Cadence information in conjunction with other sources of information might still be informative (Funato et al., 2010; Kirtley et al., 1985).

All combinations of information as presented in this experiment seemed to allow for fairly robust follow-the-leader coordination. The expansion-compression information appeared to be an important, but not sole, source of information for regulating distance. It was shown that follower behaviour in a non-competitive setting strongly depends on the locomotion characteristics of the leader. However, it was clear that the presence of segmental motion information allowed for more timely coordination. Followers were able to derive anticipatory information from the moving limbs, allowing for a tighter temporal synchronization. This did not advantage followers in terms of their spatial accuracy. The spatial accuracy was similar in the cadence and static trials, which both predominantly show the ‘honest’ visual angle. In fact, the spatial accuracy even appeared to be more stable and accurate compared to the point-light condition in which the (potentially dishonest) segmental motion information was emphasized. This highlights that followers can use different sources of information rather flexibly (a form of visual degeneracy, see for example Croft, Button, & Dicks, 2010).

3.4.2 Distance keeping strategies

Most studies examining follower leader coordination have studied locomotion in one – typically the forward – direction (Marmelat et al., 2014; Rio et al., 2014; van Ulzen et al., 2008). The current study however examined follower leader coordination in forwards and backwards walking. The effect of movement direction on spatial accuracy showed that an approaching leader was followed more consistently and accurately than a receding leader.
This finding corroborates the suggestion offered in Chapter 2 that available information from an approaching object is more specifying of distance in comparison with a receding object. It was put forward that a direction bias exists for visual angle because of the asymmetry in how visual angle changes when an object is approaching compared to receding. In short, an object that comes closer to an observer has a larger change in visual angle than an object that is receding, even if the displacement is the same. Interestingly, followers undershoot the relative distance in either direction. That is, when the leader was approaching the relative distance was smaller than the initial distance and when the leader was receding it was larger ($CD \delta$). This indicates that although distance regulation may have been regulated by visual angle information, followers nevertheless adopted a consistently conservative strategy. As there was no incentive given the current set of task constraints to risk a break in temporal synchrony or spatial accuracy in order to perform better, participants most likely adopted a safe strategy that worked ‘good enough’. Furthermore, the condition-direction interaction on the visual angle velocity suggests that the availability of segmental information reduces the effect of direction on keeping distance. The interaction between condition and direction was minimal however, suggesting that the effect of direction was not specifically related to any of the manipulated sources of information.

The effects of direction also need to be put in perspective by looking at the viewpoint effects. If the effect for direction is consistent for both viewpoints, it implies that the follower’s movement direction explains the direction effect. That is, either the follower’s locomotion direction (backwards or forwards), or the information characteristics of a receding compared to an approaching object. If however, the effect for direction is different for viewpoint (as implied by the interaction effect), it may indicate that the direction effect is governed by the leader’s locomotion direction. The main effect for viewpoint showed clearly that facing the leader’s back (F2B) improved both temporal synchronization and spatial accuracy (see Table 3.4). This was true for most conditions, particularly the point-light condition. In contrast, the sphere condition seemed to be a lot less affected by viewpoint. Arguably, followers were drawn towards the visual angle information which in viewpoint F2F may have been more specifying than segmental motion information. A further viewpoint-direction interaction was found for some of the measures of spatial accuracy. The direction effect from Chapter 2 was corroborated; an approaching leader was followed better than a receding leader. This effect persisted despite the manipulation of viewpoint. As such, this is rather strong support that as a
follower, following a leader whilst moving backwards is easier than following a leader forwards. This can most likely be attributed to the visual angle bias as explained in Chapter 2. Additionally, the viewpoint-direction interaction revealed that this direction effect affected followers more strongly when the leader was presented in viewpoint F2F. This may indicate that the mismatch between locomotion direction of the leader and follower also delimits coordination. It can thus be said that synchrony between people increases when walking in the same direction as the locomotion characteristics match more closely. In a sports setting, this may be relevant for determining defensive strategies. It appears to be advisable to move in the same direction as your attacker (i.e., walk/run forwards if the attacker is doing so too). Furthermore, regulating distance may be easier when an attacker is approaching rather than receding.

These effects highlighted that the viewpoint effect for the point-light condition was more ambiguous. To sum up, although the effect of direction was generally consistent for both viewpoints, the interaction effect revealed that a leader presented in viewpoint F2F had a larger decrease in performance when the leader was receding. A leader presented viewpoint F2B seemed to be coordinated with rather equally in either direction. Overall, these results suggest that particularly in viewpoint F2B, participants had difficulty with the point-light condition in terms of $CD \delta$. Furthermore the stability of the distance between leader and follower was highest in the sphere condition, where global motion information was emphasized most.

### 3.4.3 Flexible perception

No clear condition-viewpoint and condition-direction interactions were found. Typically the point-light and avatar conditions were performed with better than the static and cadence conditions. It only stood out that the sphere condition was hardly affected by viewpoint. Perhaps followers were strongly invited to attune to visual angle information, which was equally specifying of displacement in each viewpoint despite the mismatch in locomotion direction. On the other end of the spectrum, the point-light condition stood out for participants’ poor performance when presented in viewpoint F2B. In contrast to the static and cadence conditions, the stability and accuracy of the visual angle velocity decreased (i.e., $VE \hat{a}$ and $AD \hat{a}$ increased) in viewpoint F2B in the point-light condition. It has previously been shown that there is a strong facing bias in point-light displays (de Lussanet & Lappe, 2012). It
may explain why the point-light condition responds rather inconsistently to viewpoint regarding the spatial accuracy. Participants would have had difficulty recognizing the direction the leader was facing. This would make the expansion-compression information conflict with the segmental motion information.

Follow-the-leader coordination strategies strongly depend on the task setting. In sports, actors intend to be less predictable in order to gain a competitive advantage. For the perception-action process it is thus crucial to be able to deal with these uncertainties (deception, cf., Sebanz & Shiffrar, 2009; Williams et al., 2011). The current study examined whether changes in coordination occurred when a leader’s actions were regular or irregular (more or less predictable) in terms of the time interval lengths between turnaround points. When times between turnaround points are less regular, followers will have to tune to the optimal specifying information in order to anticipate upcoming turnaround points. The change in visual angle alone does not hold enough information to react efficiently, as was evidenced by the effect regularity had on the sphere condition. Both measures of temporal synchronization (RT and AD $\varphi$) worsened the most out of all conditions in the irregular trials compared to the regular trials. Furthermore, for the point-light condition, displaying numerous cues about upcoming actions, temporal synchronization (RT and AD $\varphi$) worsened the least out of all conditions in the irregular trials compared to the regular trials. Interestingly, the point-light condition was influenced even less than the avatar condition. Perhaps the unfamiliarity with a point-light display made the participants more cautious in general. This is highlights the importance of segmental motion information attuning locomotion in order to keep distance (Diaz et al., 2012; Fine et al., 2015). Lastly, it is important to note that regularity was only captured in terms of the interval lengths between turnaround points. To capture competitive coordination in a more representative setting it has to be taken into account that competitive behaviour also involves movements with the intention to deceive (Brault et al., 2012).

The spatial accuracy was also significantly affected by regularity. Irregular leaders were correlated with less stable and accurate spatial accuracy (both $\bar{\delta}$ and $\dot{\delta}$). However, it also appeared that distance was better kept on target overall ($CD\ \bar{\delta}$) with irregular leader. It may be that followers applied a conservative following strategy, thus undershooting the leader’s movements – when there is more uncertainty. It has previously been found that when uncertainty increases, humans take longer to make decisions (Davidson & Wolpert, 2003;
A Proposed Spectrum Loffing & Hagemann, 2014; Wolpert & Flanagan, 2010). If the followers indeed responded more cautiously, the increased spatial accuracy can then be attributed to a self-correcting mechanism, where not – or cautiously – responding can in some cases lead to a better (but not more stable) synchrony on average due to the cyclical nature of the task\(^9\). A significantly lower following velocity corroborated this explanation. Interestingly, the stability and accuracy of the spatial accuracy were least affected by regularity in the avatar condition. In the avatar condition, participants could obtain information from both ends of the spectrum. It allowed them to flexibly switch between global and local information sources as required by the task. Followers could attune more to the global motion information when the leader was regular, whereas followers could attune to more local motion information when the leader was irregular. Moreover, it may be that followers can flexibly switch between sources within movement trial. Preceding the turnaround points, followers may have relied strongly on the segmental motion information (explaining the tight temporal synchronization), whereas in between turnaround points, followers may rely more on global motion information (explaining the high spatial accuracy). It appears to be of key importance to attune to different information sources as governed by the task requirements. This finding can for example be transferred to invasion sports, where agents continuously have to compete (with opponents) and cooperate (with teammates). Actors continuously have to attune to the appropriate information sources for the type of interaction at hand (Fajen et al., 2009). Perhaps being able to adopt such flexible strategies is what construes interact-ability.

3.4.4 Limitations and future directions

The proposed spectrum with information from local to global motion information has been tested in the current study. Although some trends seem present, the proposed continuous spectrum of information may be somewhat misleading. Indeed it has been shown that different types of information provide different advantages. As such, it is suggested that being able to flexibly attune to the most effective information source may be pertinent for skilful interacting. However, it is not always clear how one condition influenced the followers differently than another. The manner in which cadence was presented did not provide a means to bridge the gap between local and motion information on the spectrum. The cadence

\(^{9}\) As the leader is about to change direction, the follower can take the ‘lead’ by standing still. Even when the follower does so too early, the leader will eventually ‘follow’. In that scenario the average distance \((CD \delta)\) will appear to be maintained (as the deviation in either direction will cancel out), but it will not appear stable \((VE \delta)\) or accurate \((AD \delta)\).
conditions were coordinated with similarly as the static conditions. It has become apparent how strongly the task constraints can influence the coordination. As such, it may be that the current task constraints were not difficult enough for the benefits (or disadvantages) of each aspect of the spectrum to be noticeable. In future research, further exploitation of key task constraints can lead to valuable insights that help understand how the dynamics of interpersonal coordination unfold.

Although the current study provides a measure to translate the leader’s covered virtual distance to a real world measure, a 2-D back-and-forwards follower-leader task is inevitably based on the assumption that this translation from on-screen motion to real world motion can be made. As such, keeping distance may be governed differently when distance is not only covered virtually. One additional aspect that has been difficult to regulate is the (virtual) starting distance between follower and leader. As Ducourant et al. (2005) showed that initial distance affects how closely distance is kept between a follower and leader; it may also be an influential factor in the current study. An attempt was made to control for this difference by varying the starting positions of the followers. Initial distance could be another task constraint that future research can examine further. Another limitation of the current task setup is that the coupling between follower and leader was mediated unidirectionally. That is, the leader was not bi-directionally coupled to the follower. In a natural situation, the follower inevitably also influences the movement of the leader (Meerhoff & De Poel, 2014). With rapidly developing technology, features such as immersed virtual reality or active gaming may in the near future allow for both realistic distance perception and including a bidirectional coupling between follower and leader in a whole-body movement task (Correia, Araújo, Cummins, & Craig, 2012; Rio et al., 2014; Varlet et al., 2013).

Lastly, the complexity of this task was reduced by having followers only move backwards-and-forwards. Although back-and-forth movements are a fundamental part of many (sub-phases) of invasion sports, it hardly ever is limited to just these movements. As has been shown in the current experiment, an alteration of any of the task constraints can lead to functionally different behaviour. It should thus be taken into account that when agents move in different directions, perception-action couplings might alter again. A spectrum of information should in theory not only be limited to one type of task; it is therefore important for future research not only to find more evidence of how different sources of information are
used for action, but also to expand to a multitude of tasks (e.g., side-to-side coordination) in order to capture a broader understanding of the principals involved in interactive coordination.

3.4.5 Conclusion

Movement systems have been shown to be flexible, adaptive and resourceful in many instances (e.g., Seifert et al., 2013; Williams et al., 2011). Also in this follow the leader task, followers have been able to effectively deal with the many types of information presented. This creativity remains difficult to grasp in experimentally controlled settings, but could potentially develop understanding of new concepts such as interact-ability. Given that participants were able to coordinate with such a large variety of information sources, it may be that skilled performance relies on the most efficient exploitation of (a combination of) this multitude in information. When applying these findings to a sports setting, the task constraints inevitably affect how information is governed for action. Nevertheless, this study has revealed that at specific instances information from one end of the spectrum appears to provide benefits over the other. In stable situations, global motion information may provide the most specifying information about relative distance. On the other hand, when movements are less predictable, it appears that attuning to segmental motion information may provide a strong temporal advantage.
Chapter 4
Lateral Following

The Dynamics of Lateral Following are Influenced by the Availability of Segmental Motion Information
4.1 Introduction

4.1.1 Lateral following

Coordinating the human body involves the control of an abundance of movement degrees of freedom and is arguably best described in terms of a complex system. Even if a biomechanical model could ever describe all kinematic properties of one movement system (Glazier & Davids, 2009), as soon as it interacts with another agent the complexity increases exponentially. Out of necessity however, many studies in the motor control literature have created simplified representations of reality in order to test hypotheses about components in isolation (Pinder, Davids, Renshaw, & Araújo, 2011). In the previous chapters, coordination was also studied in such a simplified representation of reality: the back-and-forwards movements of the leader were presented in a 2D-virtual reality display. As such, the follower’s coordination was based on the perception of the leader’s virtual displacement. Although this allowed for effective manipulation of visual information, it was based on the assumption that depth could be reliably perceived from the 2D projection. Furthermore, the previous studies examined back- and forwards locomotion to control for the mechanical complexity by restricting movement to one movement axis. The current study extends the previous studies by examining follow-the-leader behaviour in a lateral follow-the-leader task, rather than back- and forwards. By doing so, the leader’s displacement will not exclusively be virtual, which makes the 2D-3D translation redundant. Additionally, the generality of keeping distance along different movement axes can be examined. The aim of this study is to examine how global and local motion information mediates follow-the-leader behaviour in a lateral follow-the-leader task.

Although some interpersonal activities are confined to mostly back-and-forward movements (e.g., fencing), more often movements can cross several directional planes. Indeed, multidirectional movements are often essential to achieve goal-directed behaviour. For example, within ‘invasion’ sports like rugby, football and basketball, attacker-defender interactions occur along multiple axes as attackers seek to find space for attacking opportunities whilst defenders look to limit such options (Bourbousson et al., 2010a; Frencken et al., 2011). A common strategy in invasion sports is for players to use lateral movements as executed by sideways ‘shuffling’, rather than back-or-forward walking or running. Shuffling is typically executed in a crouched position (Dayakidis & Boudolos, 2006)
and allows for quick responses to an attacker’s movements, but also for unpredictable movements to create space with the defender in order to allow for plays to be made (Houck, 2003; Whitting, De Melker Worms, Maurer, Nigg, & Nigg, 2013). Particularly in basketball it is a common movement strategy to regulate lateral distance when defending (Te Wierike et al., in press).

Lateral shuffling incorporates inherently different movement characteristics compared to back- and forwards locomotion (Huang, Lin, Kuo, & Liao, 2011; Simpson, Shewokis, Alduwaisan, & Reeves, 1992). Compared to back-and-forward walking, the range of motion when lateral shuffling is decreased, hence increasing the number of steps to cover the same distance (Dayakidis & Boudolos, 2006; Huang et al., 2011). However, in particular for distance-keeping in a cyclical task, the increased number of steps may also facilitate following coordination. In back- and forwards locomotion the follower’s coordination is vulnerable if a leader changes direction whilst the follower is in the middle of the swing phase, as responses initiated mid-swing are slower and more instable (i.e., increased risk for injuries; see Dayakidis & Boudolos, 2006; Suda & Sacco, 2011) than responses once the swing phase is over. For lateral shuffling, the increased number of steps means the swing phases are typically shorter, which makes lateral shuffling more robust for unexpected turnaround points of the leader (or an attacker). Therefore, follow-the-leader coordination was predicted to be more synchronized when moving laterally compared to moving back-and-forwards. Indeed as synchrony may already be tight, additional information about the leader’s gait cycle to facilitate early responses may not be necessary. No previous studies have directly examined the information used to regulate lateral distance keeping. Whilst Meerhoff and De Poel (2014) adopted a lateral synchronization task, no leader was explicitly assigned in this task. This study revealed that dyads of agents can successfully coordinate lateral movements to achieve in- or anti-phase coordination with each other.

4.1.2 Global motion information

In addition to different movement characteristics in comparison to back- and forwards locomotion as described above, lateral distance-keeping also introduces different informational variables to regulate the coupling between follower and leader. For lateral interception, a variety of models have been tested to predict the control of movements: for example catching balls in the horizontal (or coronal) plane. One simple model states
interception can be achieved by maintaining constant alignment with the target object (e.g., Wang, McBeath, & Sugar, 2015). This model is a modification of a more commonly known strategy: the constant bearing – or eccentricity – angle (Chardenon et al., 2002; Chardenon et al., 2004). The constant bearing strategy is often used in navigation in order to predict upcoming collisions, for example in boating. Alternatively, a linear optical trajectory (LOT) where both the ‘vertical’ and ‘horizontal’ components of the optical angle are maintained constant in order to reach interception. McBeath et al. (1995) found that the LOT was the superior and most general-purpose strategy for intercepting both airborne and ground-based targets. For back- and forwards distance keeping, potential information-regulation models can also be adapted from these studies on interception (as discussed in Chapter 2 and Chapter 3).

Maintaining interpersonal distance can be considered a special case of the well-studied interceptive behaviour where optical acceleration is not only kept constant (e.g., Wang et al., 2015); for maintaining distance optical acceleration is kept constant at zero. Theoretically, nulling optical angle acceleration results in an infinite time to contact, meaning that interception – or collision – will never take place and distance will be successfully kept constant. Evidently, the current follow-the-leader task does not require participants to intercept a moving target, instead, participants have to track or keep distance with the target. For each of the coordination strategies suggested above, this implies that in terms of global motion information, the follower has to adopt a special case of LOT. That is, followers will have to null, rather than maintain constant, the alignment, bearing angle or optical trajectory.

4.1.3 Perception-action coupling for lateral movement

The perception-action strategies discussed in the previous section would each emphasise the use of global (rather than local) sources of motion information. However, when a leader’s movements become less predictable, it becomes more important to be able to extrapolate anticipatory cues from the leader’s movements (see Chapter 3). For example, it may be that specifying information can be obtained from more local information sources like the other persons’ posture. Esteves, de Oliveira, and Araújo (2011) showed that decision-making in a task simulating the one-versus-one sub-phase of basketball was constrained by the defender’s posture. Typically, ‘attacking’ a defender’s front foot (i.e., passing the defender on the side of his front foot) in basketball provides a spatial advantage for the attacker. Therefore, depending on the task-constraints, it can be argued that actors may also access local sources of information when coordinating movements laterally. The current study will therefore
contrast whether global motion information by itself will be sufficient for follower-the-leader coordination, or if segmental information is crucial for (even more) timely coordination.

### 4.1.4 Key task constraints

To further understand the dynamics of lateral follow-the-leader coordination, two constraints have been included to see if and how they may affect coordination. Firstly, viewpoint was again manipulated (see Chapter 3). The leader was presented both facing the follower and facing away from the follower. In back- and forward following, viewpoint contrasted two coordination alternatives (i.e., backwards and forwards walking), that were argued to be inherently different (Grasso et al., 1998). For lateral movements however, moving to the left and moving to the right have quite similar kinematic characteristics, as the same (homologous) muscle groups are involved. The only reasonable difference between moving to the left and moving to the right could be linked to laterality. Furthermore, the viewpoint manipulation is relevant for the social aspect of interpersonal coordination. Previously, it has been found that people are more comfortable approaching a person facing away from them than the other way around. Bailenson et al. (2003) used a immersive virtual environment to study interpersonal distance in social interactions and found that people tend to get closer to somebody when they are facing away than vice versa. This finding seems to substantiate evidence that interpersonal synchrony is affected by social constraints (Cacioppo et al., 2014). Arguably, participants might be more comfortable following a leader facing away than facing towards the follower. For the point-light condition this may be slightly more complicated. On many occasions a facing bias has been observed in point-light conditions (de Lussanet & Lappe, 2012; Weech, McAdam, Kenny, & Troje, 2014). This means that observers tend to perceive a point-light display as facing towards them even if the model is actually facing away. It can thus be hypothesized that viewpoint will not influence the performance in the point-light condition. Furthermore, as in Chapter 3, the regularity of the leader signal was also manipulated in order to replicate more and less competitive trials. It is hypothesized that the regularity of the leader signal funnels the follower’s perception to pertinent cues in the leader’s relative motion, as these may inform about upcoming turnaround points. Therefore any differences between the point-light and fixed avatar condition should become more obvious as the regularity decreases.
4.1.5 Aims and hypotheses

In this study, the coordination dynamics that result from a lateral follow-the-leader task were examined. The available visual information was manipulated by emphasizing local motion information in the point-light condition and by isolating global motion information in the fixed avatar condition. Given the characteristics of lateral shuffling, it was expected that local motion information played a less substantive role than it does in back-and-forth following. However, an effect the availability of segmental motion information on the temporal synchrony was still expected (less negative $\phi$; smaller $RT$). That said, it was hypothesized that when the regularity of the leader decreases, local, segmental motion information becomes necessary to maintain distance with the leader (i.e., an interaction between condition and regularity). Finally, the follower’s viewpoint and movement direction were presumed to play different roles compared to back-and-forth following. For lateral following, the visual angle bias may not apply and therefore no systematic effect of viewpoint was expected. Also for direction no effect was expected as moving to the left is rather similar to moving to the right. These constraints were nevertheless included to extend the findings of Chapter 3 and to rule out any interaction effects between viewpoint and direction.

4.2 Methods

4.2.1 Task

Similar to the experiments in the previous chapters, a follow-the-leader task was employed. The movements of both the leader and the followers were again restricted along one axis. However, in contrast with the previous studies, the movement axis for the current study was not towards, and away from the projection screen, instead it was parallel to the projection screen (see Figure 4.1). To clarify, a leader participant would appear in the centre of a 6 x 3 m projection screen and make lateral shuffling movements along its width. This means that instead of a virtual distance (see Chapter 3), participants were indeed maintaining a physical distance. Note that this refers to the strict lateral distance between the leader’s and the follower’s centre of mass, and not the Euclidian distance. Although at the extremes, the leader would go to either of the ends of the projection screen, the leader would most often change direction before the ends directed by the timed cues of the leader recording (see Section 4.2.3.1). Using a back projection to avoid shadows, the leader was projected facing towards (F2F) or away (F2B) from the followers. Followers were positioned 3 m away from the screen
and moved on an anti-slip mat (2 x 6 m), which implicitly confined their movement area to the calibrated measurement volume. The followers were instructed to stay directly in front of (or behind in F2B) the leader as it would move from side to side. No instructions were given about what movement type to adopt, but in all cases participants (eventually) adopted a form of lateral shuffling. When the follower was face to face with the leader (F2F), the follower would move to its left if the leader would move to its right and vice versa. On the other hand, when the follower was facing the back of the leader (F2B) the follower would move to its left when the leader would move to its left.

Figure 4.1: Schematic overview of the experimental setup of the follower (blue) and leader (red). Movement axis is indicated with the arrows. A and E denote the edges of the measurement volume. B and D denote the edges of the projection screen and the anti-slip mat the followers moved on. Every trial, participants would start at position C which was indicated with a mark on the mat.

4.2.2 Participants

For this experiment 23 male participants\(^\text{10}\) were included (aged 19-38). All participants had normal or corrected-to-normal vision and reported no known injuries that could delimit their performance whilst shuffling laterally. All participants were reasonably active as indicated by their self-rated level of fitness and weekly exercise hours (see Section Table 4.1). Additionally, all participants took part in some form of (recreational) sport. An additional participant with similar characteristics to the other participants acted as the leader participant. A 10-item handedness survey (Nicholls, Thomas, Loetscher, & Grimshaw, 2013) was

\(^{10}\)Two participants also took part in the study from Chapter 3; another two participants took part in the studies of both Chapter 2 and Chapter 3.
conducted to establish a general measure of handedness (scoring from -10, fully left-handed, to 10 fully right-handed). Three participants were fully left handed and the other participants were right handed to some degree (scoring between 7 and 10). Ethical approval was obtained from the participating institution’s human ethics committee prior to data collection, and informed consent by each participant was required prior to testing.

Table 4.1: Descriptive characteristics (mean ± SD) of participants and leader participant.

<table>
<thead>
<tr>
<th></th>
<th>Participants</th>
<th>Leader participant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>27 ± 5.4</td>
<td>22</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>83 ± 9.5</td>
<td>82</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>183 ± 7.2</td>
<td>179</td>
</tr>
<tr>
<td>Exercise (hrs/week)</td>
<td>8 ± 4.7</td>
<td>10</td>
</tr>
<tr>
<td>Self-rated level of fitness (1 low – 10 high)</td>
<td>7 ± 1.1</td>
<td>8</td>
</tr>
<tr>
<td>Handedness (-10 left- – 10 right-handed)</td>
<td>6.9 ± 6.75</td>
<td>10</td>
</tr>
</tbody>
</table>

4.2.3 Leader presentation

4.2.3.1 Recording

The leader’s movements were recorded before the main experiment. A naïve confederate, who had not participated in any of the previous experiments, was instructed to move from side to side within the 6 m width of the measurement volume. The confederate was instructed to move laterally adopting a shuffling movement and he was to change direction as dictated by an audio-signal. The timing of these cues was based on a near-random distribution with known characteristics (see Section 3.2.2). The distribution of time intervals between cues was categorized into different levels of regularity. Using two levels of regularity in Chapter 3, it was shown that regularity strongly affected the following behaviour. An extra level, which was even more irregular, was included for the current study, as the followers were anticipated to be more responsive when shuffling laterally. The first level was the most regular with a cue every 2.22 ± 0.42 s (mean ± SD), the second every 2.22 ± 0.67 s (mean ± SD) and finally the third and most irregular every 2.22 ± 0.94 s (mean ± SD). Note that these were the regularity levels the leader participant acted on, after the leader recording the actual regularity was described using the within trial variability. That is, the average (± SD) of the standard deviation of the time intervals within each trial is computed for each level of variability (see Table 4.2). Given that each trial lasts 25 seconds, the within trial average of the intervals
between turnaround points is 2.08 s, 2.20 s or 1.67 s in the high, mid and low regularity trials, respectively. The difference between the high and mid regularity trials is comparable to ‘regular’ and ‘irregular’ from Chapter 3. The low regularity trials are different from the other levels mainly because of the number of turnaround points.

Table 4.2: The three levels of regularity of the leader signals described using the variability of the time intervals between turnaround points.

<table>
<thead>
<tr>
<th>Regularity level</th>
<th>Within trial turnaround points (number)</th>
<th>Time intervals within trial SD (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>13</td>
<td>0.53 ± 0.09</td>
</tr>
<tr>
<td>Mid</td>
<td>12-13</td>
<td>0.64 ± 0.15</td>
</tr>
<tr>
<td>Low</td>
<td>16</td>
<td>0.60 ± 0.05</td>
</tr>
</tbody>
</table>

The regularity of the leader’s movements strongly affected the coordination. The leader took 82.6 ± 2.5, 83.4 ± 5.7 and 87.0 ± 3.4 steps (mean ± SD) in the high, mid and low regularity trials respectively. It is also worth noting that the leader had more turnaround points in the low regularity trials compared to the mid and high regularity trials, which explains why the within trial SD does not increase in the low compared to the mid regularity trials.

4.2.3.2 Animations

For this study several of the main components of the proposed spectrum of Chapter 3 were adopted. However, as in that study the difference between the cadence and static conditions was minimal, these conditions were omitted. The fixed avatar condition (see Figure 4.2, right) does not hold any relative motion information and thus only informs about global motion. A point-light display (see Figure 4.2, left) was used to emphasize local motion information as it predominantly requires the interpretation of the movements of the segments in relation to each other (relative motion). Furthermore, the reference moving avatar condition provided both local and global motion information as it was animated with moving limbs (see Figure 4.2, middle).
Figure 4.2: Leader forms as fitted along the proposed spectrum, with the point-light display (left), moving avatar (mid) and fixed avatar (right) conditions.

The three different conditions (see Figure 4.2) were generated for this study using Autodesk’s MotionBuilder (Autodesk Inc., San Rafael, CA, 2013). All trials were animated with both a face-to-face (viewpoint F2F) and face-to-back (viewpoint F2B) perspective. All forms were constructed from the leader participant’s movements. The moving avatar condition was based on a 15-segment model. The fixed avatar was based on the lateral displacements of the leader participant’s c7-marker only. All conditions were presented in a randomized order. Animations were generated with an artificial focal point, allowing for a more realistic optical flow (3.2.3). The focal point was set at 1.79 m (the leader participant’s height) above the ground on the projection. For the different viewpoints the camera angles were mirrored in order to keep the global visual information the same. The animations were configured to have the virtual displacement match the distance of the original recording in order to create realistic acceleration profiles.

4.2.3.3 **Replay procedure**

Each trial started with a 3-second audio tone during which the participant would stand in the middle of the measurement volume, indicated with a marker on the ground holding the T-pose (for data processing purposes). As the audio cue stopped, the participants could lower their
arms and after 2 seconds, the leader form would appear on the projection screen after which the trial began. The leader’s movements would last for 25 seconds after which the pause screen would appear for 8 seconds. After every 6 trials a 30 second break was scheduled. Contextual background was minimized by darkening the room, although the movement boundaries were clear both by the size of the projection screen and the anti-slip mat upon which participants moved.

4.2.4 Outcome variables

4.2.4.1 Data processing

Both the leader’s and the followers’ positional data was recorded using a 10 camera Motion Analysis System (Vicon Motion Systems, Inc., Centennial, CO) at a sampling frequency of 200 Hz. The lateral movements were subjected to a piecewise cubic spline interpolation to fill any gaps. The data was subsequently filtered using a second order low-pass Butterworth filter with a cut-off frequency of 5 Hz. All kinematic data were processed using MATLAB R2011a (The MathWorks Inc., Natick, MA, 2011).

4.2.4.2 Movement characteristics

As with Chapter 2 and Chapter 3, the general movement characteristics (velocity ($v$) and number of steps) were assessed alongside measures of temporal and spatial accuracy. Velocity ($v$) was calculated for each direction separately, in other words velocity was always positive. Direction was defined based on the follower’s movement direction (i.e., left or right).

4.2.4.3 Synchrony measures

The temporal synchrony was again assessed by computing the follower response times to each leader turnaround point ($RT$) and the point-estimate relative phase ($\varphi$). Spatial accuracy was assessed in terms of inter-actor distance ($IAD$, cf., $\delta_{11}$) in meters. $IAD$ was the distance along the movement axis (i.e., not Euclidian) between the follower’s and leader’s centre of mass (as estimated by the head markers). Note that inter-actor distance refers to the distance between the ‘actors’ of the experiment. That is, the pre-recorded leader (who has no agency) and the follower participant.

\[ \text{Although } IAD \text{ essentially represents the same outcome measure as } \delta, \text{ since the former represents a real-world distance and the latter represents a virtual distance, both were represented with a different symbol.} \]
Furthermore, $IAD$ was defined as such that negative values consistently indicate that the follower is lagging the leader. That is, if the leader is moving to the left and the follower is ‘behind’ (i.e., to the leader’s right), $IAD$ is negative. For $IAD$ this means that based on the leader’s turnaround points, the raw $IAD$ had to be inverted in order to have negative values represent a spatial lead by the leader. After processing, $IAD$ now indicates who is ahead of whom (i.e., positive means the leader is to the left of the follower when moving to the left, or vice versa). As such, the lead-lag relationship was indicated by the sign of $IAD$ (i.e., positive or negative). In terms of $IAD$ it is thus the followers’ aim to keep it at 0 m. A negative sign means that the leader is both temporally ($CD\varphi$) and spatially ($CD IAD$) behind the follower. Constant, variable and absolute error measures ($CD$, $VE$, $AD$, see 2.2.6.2), were computed to assess the characteristics of $\varphi$ and $IAD$ (after the data was processed). Furthermore, $RT$ and $IAD$ were analysed in each direction separately. Direction was defined from the follower’s perspective. This analysis was included to test if there was systematic effect that would counterbalance the effect of viewpoint.

Note that in contrast with the previous chapters, visual angle velocity ($\dot{\alpha}$) was not computed for the current task. Although theoretically the visual angle does change as a function of $IAD$, it was established with pilot testing that the $IAD$-related changes in visual angle are too small to reach the discrimination threshold as identified by Regan and Hamstra (1993). Furthermore, the $IAD$-related changes in visual angle would be obscured by changes as a result of up-and-down movements during sideward shuffling movements.

4.2.5 Technical issues

As part of the methodology, the same protocol to temporally align (i.e., synchronization – but to avoid confusion with the outcome measures it is addressed as temporal alignment) the leader display and the follower’s movement was used as in the previous chapters. An audio signal attached to the leader video would trigger the recording of the follower’s kinematics using a digital-analogue converter. This allows for a synchrony equal to the frame rate of the video (i.e., 25 Hz). However, due to an equipment malfunction discovered after testing was finished, this temporal alignment procedure was not functioning properly. The audio-signal that was supposed to trigger the recording had some imperfections that led to the trigger not working properly. Post-hoc examination of the experimental setup revealed triggers were systematically delayed and occurred according to a clear frequency distribution (see Figure 4.3). The delays were found to occur in steps of 81.4 ms, with the smallest delay possible 5.6
ms and the largest delay possible 3,017.2 ms. The frequency distribution allowed for an estimation of the chance that each delay would occur. Estimated temporal alignment was data driven and achieved using three steps. First, temporal alignment was estimated by linking the lag of the cross correlations to the 99.3% confidence intervals (CI) of the response times of Chapter 3 (2,216 ms). If with 95% - based on the relative frequency - certainty a delay category could be allocated to the trial it was included for step two. Only trials that could be linked to the largest delay (3,017.2 ms), could satisfy this requirement, as this delay had no likely adjacent delays. This led to a total of 283 trials of which the participant specific range of response times could be calculated. Subsequently, the process of step one was repeated with the 99.3% CI of the participant specific range of response times. Again, only the trials that could be allocated with 95% certainty were included. In total, for 452 trials temporal alignment could be estimated. Inevitably, this procedure introduces some reliability issues. However, no proof was found that a bias had occurred in selecting trials for specific participants, conditions, viewpoints or regularity levels. It is therefore assumed that the trials included have a 95% temporal alignment accuracy of 81.4 ms, in comparison to 40 ms in the previous chapters. In summary due to an equipment malfunction which led to potential temporal alignment errors out of the 828 trials originally collected, 452 were included for further analysis.

![Figure 4.3: Frequency profile of each delay (81.4 ms apart) as observed during a simulation of the experiment (n = 2702) to determine the trigger delay caused by the imperfect audio-trigger.](image)

### 4.2.6 Statistical analysis

The outcome measures were subjected to a linear mixed effects model analysis (see Section 3.2.7) using (R Core Team, 2013). Data from 452 movement trials equally distributed over 23 participants were included for analysis. For all variables the factors condition, regularity,
viewpoint were included as separate components of the regression model. Direction was also included as a factor for RT and IAD. The resulting models were thus either 3 (condition) x 3 (regularity) x 2 (viewpoint) or for the outcome measures that were also tested for direction 3 x 3 x 2 x 2 (direction) RM ANOVAs. Results were summarized using least-square means (LSmeans, Searle et al., 1980) and the corresponding standard errors (SE). Given the large number of possible post-hoc comparisons, the testing values of post-hoc tests are not always reported. Any post-hoc contrasts discussed will have been found significant ($p < 0.05$) using Tukey HSD tests. When reporting interaction effects, the relative measures related to a post hoc contrast were reported indicated by Δ.

4.3 Results

This results section is structured in two parts. The first section details the results of task constraints on lateral follow-the-leader coordination. This includes the main effects of viewpoint, regularity and direction. Subsequently, the main effects of the manipulated leader forms (condition) and its interactions with viewpoint, regularity and direction will be presented.

4.3.1 Part 1 – Task constraints

4.3.1.1 Viewpoint

Followers were better synchronized in time with leaders when presented in viewpoint F2F (see Table 4.3). Responses (RT) were significantly faster ($F(1,856) = 4.075, p = 0.044$) and the stability (VE $\varphi$; $F(1,412) = 5.683, p = 0.018$) and accuracy (AD $\varphi$; $F(1,424) = 5.801, p = 0.016$) of the relative phase (i.e., temporal synchrony) improved significantly in viewpoint F2F. Lastly there was a significant effect of viewpoint on velocity ($F(1,856) = 5.929, p = 0.015$). This effect was however strongly obscured by a direction-viewpoint interaction. No effect of viewpoint on the spatial accuracy was found.
Table 4.3: Mean (± SE) of viewpoints face-to-face (F2F) and face-to-back (F2B) on the outcome variables that were significantly affected by viewpoint. For the velocity the leader (L) and follower (F) are displayed separately.

<table>
<thead>
<tr>
<th></th>
<th>F2F</th>
<th>F2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>v (m·s⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>84.31 ± 0.31</td>
<td>1.11 ± 0.02</td>
</tr>
<tr>
<td>F*</td>
<td>1.11 ± 0.02</td>
<td>1.11 ± 0.02</td>
</tr>
</tbody>
</table>

**Temporal synchrony**

<table>
<thead>
<tr>
<th></th>
<th>F2F</th>
<th>F2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT*</td>
<td>19.88 ± 0.60</td>
<td>21.17 ± 0.68</td>
</tr>
<tr>
<td>φ (rad)</td>
<td>-0.18 ± 0.01</td>
<td>-0.20 ± 0.01</td>
</tr>
<tr>
<td>VE**</td>
<td>0.11 ± 0.00</td>
<td>0.12 ± 0.00</td>
</tr>
<tr>
<td>AD*</td>
<td>0.19 ± 0.01</td>
<td>0.20 ± 0.01</td>
</tr>
</tbody>
</table>

Significant main effects of viewpoint are indicated using * (p < 0.05), ** (p < 0.01) and *** (p < 0.001)

### 4.3.1.2 Regularity

A significant effect was found for the number of steps \((F(2,846) = 20.625, p < 0.001)\). Post-hoc contrasts revealed that followers took a significantly different number of steps at each level of regularity with the least number of steps in the low regularity trials and the most number of steps in the high regularity trials. Velocity was also significantly affected by regularity \((F(2,856) = 154.751, p < 0.001)\). The followers’ velocity was significantly different for all levels of regularity, with high regularity showing the highest velocity, and low regularity the lowest velocity. Responses \((RT)\) were significantly faster in the high regularity trials compared to both the mid regularity \((ΔRT = 3.21 \text{ ms}, t(846) = 3.185, p = 0.004)\) and low regularity \((ΔRT = 3.56 \text{ ms}, t(846) = 3.403, p = 0.002)\) trials \((F(2,846) = 6.955, p = 0.001)\). Interestingly, in terms of the other measure of temporal synchrony, the relative phase \((φ)\), no significant difference was found between the mid and high regularity trials. \(φ\) was found to be significantly more on-target overall \((CD φ; F(2,412) = 61.763, p < 0.001)\), more stable \((VE φ; F(2,412) = 150.923, p < 0.001)\) and less accurate \((AD φ; F(2,424) = 77.155, p < 0.001)\) in the high and mid regularity trials compared to the low regularity trials. The spatial accuracy was also more stable \((VE IAD; F(2,868) = 11.565, p < 0.001)\) and more accurate \((AD IAD F(2,866) = 17.085, p < 0.001)\) in the high and mid regularity trials compared to the low regularity trials. No significant regularity effect was found on \(CD IAD\). Taken together, these results indicate that participants were most successful in the high regularity trials. For most aspects \((CD φ, VE φ, AD φ, VE IAD and AD IAD)\) the mid regularity trials were more
on target and stable than the low regularity trials, but for RT and CD IAD the difference was not so clear.

Table 4.4: Mean (± SE) of regularity on the outcome variables that were significantly influenced by regularity. For the individual measures the leader (L) and follower (F) are displayed separately.

<table>
<thead>
<tr>
<th>Regularity</th>
<th>High</th>
<th>Mid</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steps (number)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>82.36 ± 0.63</td>
<td>83.5 ± 0.59</td>
<td>87.06 ± 0.36</td>
</tr>
<tr>
<td>F***</td>
<td>78.32 ± 1.39ab</td>
<td>74.41 ± 1.34a</td>
<td>75.86 ± 1.32</td>
</tr>
<tr>
<td>v (m·s⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>1.28 ± 0.01</td>
<td>1.21 ± 0.01</td>
<td>1.04 ± 0.01</td>
</tr>
<tr>
<td>F***</td>
<td>1.21 ± 0.02abc</td>
<td>1.15 ± 0.02ac</td>
<td>0.96 ± 0.02bc</td>
</tr>
<tr>
<td>Temporal synchrony</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT (ms)***</td>
<td>18.26 ± 0.84ab</td>
<td>21.48 ± 0.69a</td>
<td>21.83 ± 0.74b</td>
</tr>
<tr>
<td>φ (rad)</td>
<td>CD*** -0.15 ± 0.01b</td>
<td>-0.16 ± 0.01c</td>
<td>-0.25 ± 0.01bc</td>
</tr>
<tr>
<td>VE***</td>
<td>0.09 ± 0.00b</td>
<td>0.09 ± 0.00c</td>
<td>0.17 ± 0.00bc</td>
</tr>
<tr>
<td>AD***</td>
<td>0.16 ± 0.01b</td>
<td>0.17 ± 0.01c</td>
<td>0.26 ± 0.01bc</td>
</tr>
<tr>
<td>Spatial accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IAD (m)</td>
<td>CD -0.08 ± 0.01</td>
<td>-0.07 ± 0.01</td>
<td>-0.07 ± 0.01</td>
</tr>
<tr>
<td>VE***</td>
<td>0.2 ± 0.01b</td>
<td>0.21 ± 0.01c</td>
<td>0.22 ± 0.01bc</td>
</tr>
<tr>
<td>AD***</td>
<td>0.2 ± 0.01b</td>
<td>0.19 ± 0.01c</td>
<td>0.22 ± 0.01bc</td>
</tr>
</tbody>
</table>

Significant main effects of viewpoint are indicated using * (p < 0.05), ** (p < 0.01) and *** (p < 0.001) Significant (p < 0.05) post-hoc differences are indicated with a (high and mid regularity), b (high and low regularity), and c (mid and low regularity)

4.3.1.3 Direction

The followers’ movement direction (see Table 4.5) has a smaller influence than viewpoint and regularity. A significantly higher velocity was found when the follower moved to the right (F(1,856) = 79.014, p < 0.001) which was accompanied by a smaller deviation from the target distance (CD IAD; F(1,862) = 8.9185, p = 0.003) and higher accuracy of the following distance (AD IAD; F(1,866) = 5.221, p = 0.023). No effect was found for the number of steps, RT or φ.
Table 4.5: Mean (± SE) of direction on all outcome variables. For the individual measures the leader (L) and follower (F) are displayed separately.

<table>
<thead>
<tr>
<th></th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v (\text{m} \cdot \text{s}^{-1}))</td>
<td>L 1.12 ± 0.00</td>
<td>1.23 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>F*** 1.04 ± 0.02</td>
<td>1.18 ± 0.02</td>
</tr>
</tbody>
</table>

**Spatial accuracy**

|                  | CD**, +++ | -0.08 ± 0.01 | -0.06 ± 0.01 |
|                  | VE       | 0.21 ± 0.01  | 0.21 ± 0.01  |
|                  | AD*, +++ | 0.21 ± 0.01  | 0.20 ± 0.01  |

Significant main effects of viewpoint are indicated using \(^* (p < 0.05), ** (p < 0.01)\) and \(*** (p < 0.001)\).

Significant viewpoint-direction interactions are indicated using \(^* (p < 0.05), ** (p < 0.01)\) and \(*** (p < 0.001)\).

4.3.1.4 Viewpoint-direction interaction

The effect of direction on the follower’s coordination was rather subtle, but a small improvement (i.e., \(CD IAD\) closer to target and smaller \(AD IAD\)) can be observed when the follower moved to the right (see Table 4.5). Viewpoint had no clear main effect on the spatial accuracy, and no interactions between viewpoint and direction were found for the temporal synchronization. The viewpoint-direction interaction was found significant for both for \(CD IAD\) \((F(1,862) = 51.692, p < 0.001)\) and \(AD IAD\) \((F(1,866) = 22.568, p < 0.001)\). Closer inspection of the post-hoc contrasts revealed that in viewpoint F2F, \(CD IAD\) got significantly further from the target when moving to the right \((\Delta CE IAD = 0.04 \text{ m}, t(862) = , p < 0.001)\), whereas in viewpoint F2B, \(CD IAD\) got significantly closer to the target when moving to the right \((\Delta CE IAD = 0.07 \text{ m}, t(862) = 7.189, p < 0.001)\) – see Figure 4.4 (top panel). The accuracy of the spatial accuracy increased (i.e., decreased \(AD IAD\)) significantly when moving to the right, but only in viewpoint F2B \((\Delta AD IAD = 0.02 \text{ m}, t(866) = 4.069, p < 0.001)\) – see Figure 4.4 (bottom panel). These results suggest that the subtle differences that were found for direction can largely be explained by the leader’s movement direction. The spatial accuracy is kept slight better when leader is moving to its right.
4.3.2 Part 2 – Effect of leader information

In this section the effect of the type of leader form (i.e., condition) on the followers’ performance will be presented. First, an overview is given of the main effects for condition and all outcome variables (see Table 4.6). Then, these main effects and accompanying significant interaction effects with either of the task constraints (viewpoint, regularity and direction) are presented.

Figure 4.4: Overview of the significant viewpoint-direction interactions for CD IAD (top) and AD IAD (bottom). Significant differences for direction are indicated for F2F (*) and F2B (+) separately.
Table 4.6: Mean (± SE) are displayed for each outcome variable. Note that interactions might influence the appearance of the condition effect as perceived from the table.

<table>
<thead>
<tr>
<th></th>
<th>Point-light</th>
<th>Moving avatar</th>
<th>Fixed avatar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steps (number)</td>
<td>L</td>
<td>84.31 ± 0.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>76.08 ± 1.35</td>
<td>76.39 ± 1.35</td>
</tr>
<tr>
<td>v (m·s⁻¹)</td>
<td>L</td>
<td>1.18 ± 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F⁻¹,²,³</td>
<td>1.11 ± 0.02</td>
<td>1.10 ± 0.02</td>
</tr>
</tbody>
</table>

Temporal synchrony

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RT (ms)¹</td>
<td></td>
<td>19.20 ± 0.80</td>
<td>19.47 ± 0.80</td>
</tr>
<tr>
<td>φ (rad)</td>
<td>CD</td>
<td>-0.18 ± 0.01</td>
<td>-0.18 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>VE</td>
<td>0.12 ± 0.00</td>
<td>0.12 ± 0.00</td>
</tr>
<tr>
<td></td>
<td>AD</td>
<td>0.19 ± 0.01</td>
<td>0.19 ± 0.01</td>
</tr>
</tbody>
</table>

Spatial accuracy

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>IAD (m)</td>
<td>CD</td>
<td>-0.07 ± 0.01</td>
<td>-0.08 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>VE</td>
<td>0.21 ± 0.01</td>
<td>0.21 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>AD⁻¹,²</td>
<td>0.20 ± 0.01</td>
<td>0.20 ± 0.01</td>
</tr>
</tbody>
</table>

Significant effects (p < 0.05) for: ¹ Condition, ² condition-viewpoint, ³ condition-regularity, ⁴ condition-direction. Significant post-hoc differences for condition are indicated with a (point-light and moving avatar), b (point-light and fixed avatar), and c (moving avatar and fixed avatar).

4.3.2.1 Movement characteristics

All leader forms were based on (a selection of) the same leader trajectories, which means that the number of steps and velocity were also the same for each leader form¹². Although no main effect for condition was found for the number of steps, there was a significant condition-regularity interaction (F(4,846) = 4.440, p = 0.001). The number of steps taken in the moving avatar and point-light condition did not differ significantly at any of the regularity levels. The number of steps in the fixed avatar condition was more drastically affected by regularity compared to the other conditions: in the high regularity trials followers took significantly more steps compared to all conditions at both the mid and low regularity levels. In the mid regularity trials participants took significantly less steps compared to all conditions in the high regularity trials.

¹² For the fixed leader, steps are only shown by the leader’s acceleration pattern. No limb motion was shown, so strictly speaking the leader form did not step.
For the follower’s velocity, both a condition-viewpoint \((F(1, 856) = 7.277, p < 0.001)\) and a condition-regularity \((F(4, 856) = 4.479, p = 0.001)\) interaction were found on top of the main effect for condition \((F(2, 856) = 28.013, p < 0.001)\). For all conditions, the participants’ \(v\) was significantly lower in the low regularity trials compared to the mid and high regularity trials. Only in the fixed avatar condition was \(v\) lower in the mid compared to high regularity trials \((\Delta v = 0.19 \text{ m} \cdot \text{s}^{-1}, t(856) = 7.730, p < 0.001)\). The condition-viewpoint interaction revealed no significant post-hoc contrasts. For the point-light condition, viewpoint only trended to an effect \((p = 0.055)\).

### 4.3.2.2 Temporal synchrony

Although \(\varphi\) was not significantly affected by condition, the other measure for temporal synchrony \((RT)\) was. A main effect for condition on \(RT\) \((F(2, 846) = 7.101, p < 0.001)\) was revealed (see Figure 4.5). Post-hoc contrasts showed that responses were significantly slower in the fixed avatar condition compared to both the point-light \((\Delta RT = 3.70 \text{ ms}, t(846) = 3.846, p < 0.001)\) and moving avatar \((\Delta RT = 3.43 \text{ ms}, t(846) = 3.548, p = 0.001)\) condition. No further interactions with condition were found for \(RT\). In absence of a significant effect for \(\varphi\), the \(RT\) effect is correlated with the length of each movement cycle. This means that the slowest responses in the fixed avatar condition (that led to the high \(RT\)), would have happened during the relatively longer movement cycles. The effect of the slow response on \(\varphi\) would then be diminished, because it is proportional to the length of the movement cycle.

![Figure 4.5: Main effect for condition on RT, significant post-hoc differences are indicated (*)](image)

Figure 4.5: Main effect for condition on \(RT\), significant post-hoc differences are indicated (*).
4.3.2.3 Spatial accuracy

For the spatial accuracy no main effects for condition were found. Only a significant condition-direction interaction was found for \( AD IAD \ (F(2,866) = 4.231, p = 0.015) \). The interaction effect reveals that there are subtle differences between conditions. In the post-hoc contrasts it became apparent that for the fixed avatar condition, \( AD IAD \) was higher (i.e., less accurate) when moving to the left compared to moving to the right (\( t(866) = 2.918, p = 0.042 \)). No differences were found between conditions.

4.4 Discussion

The current study examined how followers use different types of information for regulating distance in a lateral follow-the-leader task. Furthermore, it was considered how the relative use of these types of information was influenced by the regularity of the leader (as an analogy for more competitive interaction situations). Viewpoint was also manipulated in order to confirm whether any direction effects were attributed to the leader’s or the follower’s direction. The results showed that although the availability of segmental motion coordination allowed for a tighter temporal synchronization, this did not significantly influence the spatial accuracy. The early responses that were driven by local motion information were as often detrimental as beneficial to keeping distance. Overall, it seems that lateral distance regulation is thus predominantly mediated by global motion information.

4.4.1 Space-time discrepancy

The most prominent aspect of the current study is that whilst improved temporal synchrony can be observed in certain conditions, this does not always lead to better spatial accuracy (i.e., a kind of ‘space-time discrepancy). In general, the temporal synchrony was found to be tighter when segmental motion information was present (i.e., point-light and moving avatar condition) compared to when no segmental motion was available (i.e., fixed avatar condition). It is worth noting that the lack of a significant condition effect on \( \varphi \) in combination with a significant effect on \( RT \), implies that the longer a participant had to observe the leader (i.e., a large interval in between turnaround points), the faster the participant could respond. This is comparable with the effect found in Chapter 2, where participants initially responded slow to local motion information, but as the trial progressed (i.e., participants had been observing the leader for longer) participants responded faster when local motion information was available.
It appears that local motion information becomes more useful for responding fast if a longer period of stable coordination precedes a critical event (i.e., turnaround point). This corroborates findings from a study on one-handed catching where Panchuk, Davids, Sakadjian, MacMahon, and Parrington (2013) showed the availability of early visual information changes the visual search behaviour and allows for earlier onset of hand movements.

In line with the previous chapters, the temporal advantage in the current study did not correlate with spatial accuracy. With anticipatory behaviour, there is a risk of anticipating incorrectly or prematurely. For the current task, there was no trade-off for responding too early (or too late). That is, the risk was not explicated as there was no noticeable downside to responding ‘incorrectly’. Perhaps only the perceived mismatch provided such feedback, but no feedback was given about any errors (if there were any). To illustrate this point, Figure 4.6 shows some exemplar data that may explain the trade-off of responding quickly. In the top panel the positional data of three different trials is shown, each with the same leader movement pattern (black), but presented either with the point-light (red), moving avatar (blue), or fixed avatar (green) leader. Especially for the turnaround point between 10 and 15 seconds, it can be seen that the participant reacted in anticipation of the turnaround point in the moving avatar condition. Although the participant in the moving avatar condition does respond faster than the other conditions, it actually corresponded with a larger deviation in the IAD, as can be observed in Figure 4.6.
Follow the leader

Figure 4.6: Exemplar data showing the space-time contradiction, i.e., how an increased temporal synchrony can lead to a decreased spatial accuracy (within trial averages are shown). Top: positional data of the leader and followers in the different conditions. Bottom: the corresponding IAD, ‘Right’ and ‘Left’ indicate the follower’s movement direction.

In the current task, responding early always led to an increased temporal advantage, even when the early response was ‘too’ early and led to a deviation in IAD. Only when early responses were correct (that is, not too early or too late), it would lead to an improved spatial accuracy. Given the contradicting spatial and temporal synchrony effects of condition, it can be assumed that although followers were enticed to respond early, their responses were as often detrimental for the spatial accuracy as they were beneficial. It can thus be argued that although humans may be able to identify (faked-) actions based on changes in action kinematics (Tidoni, Borgomaneri, Pellegrino, & Avenanti, 2013), coordinating with global information leads to less risky and more robust following behaviour (e.g., Huys et al., 2009). A temporal advantage may be gained from local information sources, but as shown in other studies it requires skill to effectively attune to such local information, as it is prone to misleading information or deception (Sebanz & Shiffrar, 2009). In the current task participants attuned to non-specifying segmental motion information, however, depending on the task constraints segmental motion information may also be detrimental for coordination.
Evidently, in sports the trade-off between incorrectly responding (i.e., too early – or too late) can lead to a competitive disadvantage.

### 4.4.2 Viewpoint and direction

In lateral following, the orientation of the leader (i.e., F2F or F2B) affected followers differently than in back-and-forwards following. For back-and-forwards following, viewpoint F2B clearly resulted in both a tighter spatial and temporal synchrony. In the current study, participants responded faster when the leader was presented in viewpoint F2F, in contrast to Chapter 3. However, viewpoint did not affect the spatial accuracy. Faster responses in the previous chapters were largely attributed to a mismatch in locomotion direction when the leader was presented in viewpoint F2F. For lateral movements this mismatch is less strong. Furthermore, the lateral follow the leader task arguably resembled a common sub-phase of many invasion sports, which many participants were familiar with. In invasion sports defenders typically face their attacker when for example defending in a one-versus-one sub-phase of basketball. As they will be more familiar with mirroring (i.e., F2F), rather than copying (i.e., F2B), movements, participant may have been able to better respond to the leader’s movements in viewpoint F2F (Cole, Chan, Vereijken, & Adolph, 2013).

In Chapter 3, the effect of viewpoint in back-and-forwards following was partially attributed to the inherent discrepancy between walking forwards and walking backwards. As backward and forward movement hold different characteristics, a leader that is performing the same locomotion direction at the same time (i.e., F2B) may be easier to follow. For lateral following however, the discrepancy between locomotion directions is less clear if not obsolete: shuffling to the left or right uses homologous muscle groups and is not as clearly different from each other as back- and forwards locomotion. As such, the difference between shuffling left and shuffling right was marginal. The interaction between viewpoint and direction however, was insightful (see Figure 4.4). In terms of spatial accuracy the interactions indicated that the leader’s movement direction is correlated with spatial accuracy. More specifically, when the leader is moving to his right (i.e., to the follower’s left in viewpoint F2F) followers best maintained distance. This implies that there is no mismatch between movement information of moving to the left or right (cf., visual angle bias). The effect was not further corroborated for velocity, which could have provide a possible explanation for this direction effect. Alternatively, handedness, or more broadly laterality, may play a role in explaining this difference, but the current study was not designed to
address this issue properly. Perhaps future research can examine how laterality differences may influence sideward following.

4.4.3 Regularity

An irregular leader is expected to force the followers into using the most specifying source of information (cf., Brault et al., 2012). However, as no clear condition-regularity interaction was found, the followers either found this most specifying source in all conditions, or the task was not sensitive enough to explicate the difference. The manipulation of regularity is grounded in a large difference between the number of turnaround points made by the leader. This results in more frequent acceleration and deceleration, which subsequently results in a lower average velocity and a smaller distance covered in the same 25 s. When less distance is covered it creates an inherent bias for IAD to be closer to target. The increased number of turnaround points also explains how RT can be equal in mid and low regularity trials, whereas \( \varphi \) is better in the mid regularity trials. As \( \varphi \) is scaled for the time of a full cycle, an absolute deviation of similar magnitude (i.e., RT) can result into a relatively larger deviation in \( \varphi \).

It is furthermore interesting to note that only for some outcome variables (number of steps and velocity) a significant interaction was found with regularity and condition. The number of steps was most affected in the fixed avatar condition, arguably because the follower could not mimic the steps of the leader (Ducourant et al., 2005). This means that although the lack of segmental motion information influenced the followers, it had no effect on the task-related outcomes. Overall, it appears that followers had enough information in either of the conditions to deal with the irregularity.

4.4.4 Limitations

Although there is a known issue in this study with the data collection (see Section 4.2.5), reducing the accuracy of the temporal alignment between the virtual leader and the participants by at least 50% compared to the studies from Chapter 2 and Chapter 3, it is safe to say that the effects found were robust for any bias introduced by this error. However, one has to be cautious interpreting the magnitude of the outcome measures for temporal synchrony. It is possible that the improvised temporal alignment procedure resulted in the selection of trials in which the temporal synchrony was best. As there was no bias found for the number of trials selected in either condition, there is no reason to believe that any of the effects found were due to a bias introduced by the temporal alignment procedure. When
interpreting these results, it has to be taken into account that perhaps only the more successful trials have been included and that therefore some significant effects may have been missed.

### 4.4.5 Conclusion

The findings of this study provide a useful and novel insight as to how lateral distance keeping is governed by visual information. A temporal advantage is likely to be obtained when paying attention to the segmental motion information, however, the temporal advantage may not always lead to a spatial advantage. As such, followers may benefit from attuning to the more ‘honest’ global motion information (Brault et al., 2012). Global motion information holds sufficient information for coordination, therefore, more local information sources are not directly necessary to effectively regulate lateral distance. Future research should focus on how the balance between temporal and spatial accuracy can be put under pressure by forcing participants to choose more risky strategies. In (invasion) sports, athletes often have to sacrifice one type of synchronization for the other, as otherwise they may be defeated. Arguably, in invasion sports the most skilful interactors have a higher capacity of dealing with that increased pressure. The current study provides a rich contribution to understanding the perception-action coupling for interpersonal coordination: it has been shown that for lateral following segmental motion information improves temporal synchrony. This implies that there is indeed relevant information available on a local level. Future research should further explore how this temporal benefit can be picked up when movements become more competitive, or even deceptive.
Chapter 5

Overall Discussion
5.1 Introduction

In this final chapter the main findings of the three experimental studies from the current thesis are summarized. This provides an opportunity to link the findings of the different studies. Furthermore, the limitations of the current thesis will be discussed, along with possible directions for future research. Finally, the major contributions and implications of this research programme will be addressed in the context of perception-action research and interpersonal coordination. The aim of this thesis was to examine distance regulation through whole-body movements in a follow-the-leader task. In each study, available information of the leader was manipulated to observe its effect on the followers’ movements and subsequently infer how such information governs coordination between leader and follower.

5.2 Main findings

5.2.1 Chapter 2

The first experimental study (see Chapter 2) addressed the specificity of visual angle information for keeping distance with a virtual leader who was moving backwards and forwards. The leader, which was either presented as a fully animated avatar or as a sphere, moved towards or away from the follower. The avatar conveyed information for distance keeping through the change in optical size (i.e., global motion information) and through the relative movements of the limbs (i.e., local motion information). The sphere on the other hand only informed about relative distance via its perceived change in optical size. Followers were instructed to maintain a constant distance with the leader. The temporal and spatial accuracy of the follower-leader dyads were analysed to establish the effect of the isolation of global motion information. Results indicated that followers were able to regulate distance based on visual angle information in isolation (i.e., sphere leader). In fact, the spatial accuracy was even tighter when only global motion information was available. Although the segmental (i.e., local) motion information available in the avatar condition allowed participants to be more synchronized in time, it did not improve the spatial accuracy compared to the sphere condition. Furthermore, it appeared that the specificity of the visual angle information depended on the movement direction. When global motion information was isolated in the sphere condition, keeping distance with an *approaching* leader was done more accurately than with a *receding* leader. It was posited that this may be attributed to a visual angle bias. The
visual angle changes more quickly when distance is *decreasing* compared to when distance is *increasing*. An alternate explanation, which requires further investigation, may be that the difference resulted from the leader walking forwards whilst the follower was walking backwards, and vice versa, since the follower and leader were facing each other. In summary, this study extended previous research on interceptive actions by showing that global information may also be a dominant source of information for keeping distance. Precisely what role local motion information plays for such a task was still unclear at this stage.

### 5.2.2 Chapter 3

In the first study, two information sources on opposite ends of a potential spectrum were contrasted. Chapter 3 addressed the possibility that in fact a range of information sources can be used by followers, from local to global motion information. The second study revealed that followers could best keep distance when both local and global motion information were present. In the point-light condition (emphasizing local, but not excluding global, motion information) participants generally performed better than when global motion information alone (a combination of cadence and expansion-compression related information) was available. Furthermore, as the leader’s movements got more irregular with more frequent direction changes (or “turnarounds”), more relative benefit from local motion information sources was shown. It was argued that the local, segmental motion information provided anticipatory cues which are absent from global information. The manipulation of regularity provided an analogy for competitive coordination, as the leader’s movements were less predictable. As such, more pressure is put on the followers to attune to the information that best specifies upcoming actions. When segmental motion was available, followers could better cope with the irregularity, highlighting the value of segmental motion information. It is thus inferred that attunement to segmental motion information better allows individuals to anticipate the future actions of others. However, other studies (e.g., Canal-Bruland et al., 2011; Williams, Huys, Canal-Bruland, & Hagemann, 2009) have shown that despite segmental motion information being informative of future actions, it can also lead to the follower being more vulnerable to deceptive actions. As local motion information also has the potential to be “dishonest” (Brault et al., 2012), interact-ability may be construed of flexibly attuning to the most effective source of information only when it is honest.
In line with Chapter 2, further support was found for better spatial accuracy with an approaching compared to a receding leader in Chapter 3. Interestingly, this effect was dampened when segmental motion was available in addition to global motion information. This corroborates findings of the first study where movement direction (i.e., approaching vs. receding) was suggested to create a bias for the specificity of the visual angle-based information. However, an additional effect was found from the change in the follower’s viewpoint. In addition to the visual angle bias, following a leader that is walking in the same direction (viewpoint F2B; both the leader and follower walk forward or backward simultaneously) also facilitates distance-keeping.

5.2.3 Chapter 4

In the third study (see Chapter 4) the generality of the follower dynamics of Chapter 2 and Chapter 3 was examined in a lateral version of the follow-the-leader task. Human movements are not (necessarily) limited to movements along the back-and-forwards axis, therefore expanding distance-keeping to a lateral following task will provide a broader examination of the ‘keeping distance’ task in general. Furthermore, by changing the movement axis, followers have to follow a virtual leader that in fact is covering a physical distance as it moved from one side of the projection screen to the other. In the back-and-forward virtual reality tasks it was presumed that participants could interpret the 2D leader display as 3D motion. In the lateral following task the assumption of a 2D-3D translation is avoided. Additionally, the estimation of virtual distance ($\delta$) is also avoided in this lateral follow-the-leader task. Results revealed that there was an apparent contradiction between the spatial and temporal synchronization. Although temporal synchronization was facilitated by local motion information, it did not lead to an improvement of the spatial accuracy. It was suggested that this resulted from the temporal advantage being applied incorrectly as often as it was applied correctly. That is, segmental motion information indeed provided anticipatory cues, but their availability did not always lead to correct anticipation. This is fundamental in a competitive setting where an actor may use deceptive (local) motion information to provoke such incorrect anticipation in order to gain an advantage over the opposition.

For lateral following a clear interaction was found between viewpoint and direction, indicating that only the leader’s movement direction had an influence on following behaviour. The interaction excluded any systematic viewpoint effect, unlike for back-and-forth follower-
the-leader coordination. In back-and-forwards following, viewpoint strongly affected coordination because of both the direction bias of visual angle and the discrepancy between the follower’s and the leader’s movements. However, as laterally shuffling to the left is mechanically fairly similar to shuffling to the right, the factors that facilitate following a leader from viewpoint face-to-back (F2B) in back-and-forward following no longer play a role in lateral following. In fact, a slight advantage of following a leader in viewpoint face-to-face (F2F) was found for lateral following. This is attributed to followers being more familiar with mirroring a person F2F, given it is a common occurrence in attacker-defender dyads in invasion sports. However, it may well be that a social constraint underlies this effect. It has been repeatedly shown that (Euclidean) distance between persons is perceived differently when facing each other, rather than facing the other person’s back (de Lussanet & Lappe, 2012; Weech et al., 2014). Although in the current task no social constraints were manipulated, previous experiences of the participants may have transferred to the current task. Finally, this study has corroborated the finding Ducourant et al. (2005), who showed that followers can regulate distance with a leader without mimicking a leader’s gait. Instead, followers regulate distance based on a global level, rather than at the level of the segments (i.e., step characteristics). For lateral following, it was shown that although the presence of local information does affect a follower’s gait, without such information followers find a gait pattern that does not resemble the leader’s gait (as they could not observe it) but is equally effective in keeping distance.

5.3 Limitations and future research

5.3.1 Virtual reality

From an ecological psychology perspective, studies that combine action and perception provide interesting insights in how the perception-action coupling governs coordination. Therefore, in this research programme a task was chosen where the movement responses were recorded to a manipulation of visual information (i.e., by using a version of virtual reality). Although its benefits are clear (see for example Section 1.4.3), there are some important limitations that need to be taken into account when considering the implications of this work. First of all, this study does not use an immersive virtual reality, in which the third dimension of a virtual reality is simulated using, for example, a head-mounted display (e.g., Bailenson et al., 2003). As such, the 2D display of the leader’s movements in this study is assumed to be
interpreted by the follower as a leader moving in 3D. This translation may make the coordination less representative of interpersonal coordination in real life. A key attribute of virtual reality is that it allows for a complete control over what information is available from the environment. It even allows for the direct comparison of two types of information by making them more or less incongruent. Rio et al. (2014) manipulated distance perceived through binocular disparity to be different from distance perceived through optical expansion. As such, they showed that when keeping distance, humans predominantly rely on optical expansion rather than binocular disparity. The current rapid development of 3D technologies will make immersive virtual realities more readily accessible in the near future. Indeed, many low-cost, open source alternatives have become available (e.g., Google Cardboard), which should allow for studying interpersonal coordination in an even more representative setting.

Another aspect to be aware of in the current virtual reality setting is that the coupling between the follower and leader was unidirectional. That is, the movements of the leader were pre-recorded and not responsive to the movements made by the follower. It has been previously shown that even when roles are clearly allocated, the coupling between persons is bi-directional (Meerhoff & De Poel, 2014). Arguably, this influenced the representativeness of the inter-personal’ coordination. The current task technically did not entail coordination between persons; instead it was a tracking task of a person-like object. It may well be that especially this bi-directionality is important for the dynamics of distance-keeping in interpersonal coordination. Particularly when linking interpersonal coordination to interact-ability, the skillset presumably consists of being susceptible to the most specifying information and being able to convey information about one’s own actions either to deceive an opponent or to cooperate with a teammate. In other words, the lack of bi-directional coupling reflects a lack of agency of the leader. Arguably, interpersonal coordination derives a large part of its complexity based on two (or more) interacting components with agency. The influence of agency on the coordination dynamics may be variable. In more strictly guided interpersonal ‘routines’ (e.g., marching bands, or some dance forms), the coordination between persons is restricted to what is pre-determined as the routine. Some studies have attempted to modulate the agency between interacting components by implementing a virtual

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13 In the first study (Chapter 2) a bi-directional condition was initially included. A live confederate leader walked back-and-forth guided by audio cues. However, as the distance between leader and follower was different from the virtual settings (sphere and avatar), and because the analysis of spatial accuracy could not be compared with the virtual settings it was decided not to include this data in the thesis. Additionally it appeared that the confederate live leader behaved rather differently with each follower participant.
partner (e.g., Kelso, de Guzman, Reveley, & Tognoli, 2009). Future research on interpersonal coordination can gain a lot of ground by becoming more familiar with how interactions are mediated between people. Thus far, the most notable observation is that interactions between people are not necessarily symmetrical (Meerhoff & De Poel, 2014; Peper, Stins, & de Poel, 2013), similar to coupling within persons (de Poel, Peper, & Beek, 2007; de Poel, Peper, & Beek, 2006). As such, using virtual reality settings can further the understanding of interpersonal coordination by using, for example, well-instructed ‘confederates’, robots, or even virtual leader of which the dynamics can be fully specified.

5.3.2 Cooperation-competition

Agency is also of particular importance in sports, where coupling between persons is not only based on cooperation, but also on competition. As such, competing agents generally aim to achieve the opposite task goals. For example, in ball sports like basketball an attacker is typically trying to break dyadic stability and invade territory whereas a defender is trying to maintain stability and protect physical spaces (Araújo, Davids, Bennett, Button, & Chapman, 2004). In a cooperative setting, agents have to coordinate together in order to best achieve the task goal. This radically changes the nature of the interactions between members of the same team compared to interactions with their competitors. For the perception-action coupling, this means that being sensitive (attuning) to certain types of information does not necessitate acting upon said information as the most successful response. This becomes key when detecting deceptive movements (Brault et al., 2012; Canal-Bruland, van der Kamp, & van Kesteren, 2010; Makris & Urgesi, 2015; Williams et al., 2011). Although the current research programme did not specifically address cooperation and competition, it was put forward to explain the effect of one of the manipulated task constraints (regularity). It was shown in Chapter 3 that a more irregular, or competitive, leader was better coordinated with when segmental motion information was available. Although it was found that the non-specifying segmental motion information facilitated following an irregular leader, it was noted that this source of information could also be used deceptively by a leader. It was inferred that skilful interacting is comprised of being able to effectively distinguish between honest and deceptive information. It should be noted however, that an actor may be able to easily deceive opponents that attune to –potentially dishonest – local motion information.
5.3.3 Future directions for interpersonal coordination

A critical note for interpersonal coordination research as informed by an ecological dynamical systems approach is that it has proven difficult to tackle coordination problems with universal or law-like solutions (e.g., Passos et al., 2009). Some attempts have been made to obtain potentially new ways to quantify team performance (Frencken et al., 2012; Glazier, 2010; Passos et al., 2008) and these approaches clearly expand the understanding of movement systems based on merely notational analysis. However, given its immense complexity, defining rules that universally apply to many types of interpersonal coordination (Turvey, 1990) seems to be a task too challenging for interpersonal coordination research. Perhaps an area with interpersonal coordination that has been underexposed is the social aspect of interpersonal coordination (see for some interesting exceptions, Oullier et al., 2008; R. C. Schmidt et al., 1994). Interpersonal synergies (Riley, Richardson, Shockley, & Ramenzoni, 2011) may be partially governed by the extent to which one agent ‘matches’ with another – in this specific case visually attractive – co-actor (Zhao et al., 2015). Furthermore, interpersonal coordination influences the perception of the social interaction as well (Soliman, Ferguson, Dexheimer, & Glenberg, 2015). In musical performances, it has been shown that familiarity of the co-actors affects performance (Ragert, Schroeder, & Keller, 2013). For interpersonal coordination in sports, this may imply that developing an understanding of another agent’s action capabilities could facilitate forming more effective partnerships (or ‘hot links’). As such, the social aspect of coordination (Marsh, Richardson, & Schmidt, 2009) may also be an important component of skilful interacting.

The current research programme adopted a whole-body movement task to examine the effect of certain types of visual information. Other approaches may provide further insight into the specific type of visual information used. It, is for example, possible to make inferences about what information is used for action based on eye movements using an eye-tracker (e.g., Vickers, 2009). This allows for an accurate estimation of what an agent visually focussed on, even in natural settings given the development of a mobile eye tracker (Franchak, Kretch, Soska, & Adolph, 2011; Hayhoe & Ballard, 2005). Most promising is perhaps the combination of eye tracking and virtual reality research (e.g., Carletta et al., 2010). Knowing what participants look at and being able to manipulate the appearance of visual information in the virtual world may give promising insights in the perception-action coupling.
Follow the leader

The latest trends in adopting a dynamical stance and furthering the understanding of interactions in sports may be provided by so called ‘big data’ studies (Davids et al., 2014; Millington & Millington, 2015). In this type of approach, a computer-learning algorithm is used to process vast amounts of data of ‘real’ behaviours (for example match data). By analysing enough scenarios that can be coded similarly, it is possible to create data driven pattern recognition sequences that allow for a thorough and objective tactical analysis of game play (e.g., Chang et al., 2014; Maheswaran et al., 2014). By adopting a big data approach, it is hypothetically possible to analyse data without any a-priori assumptions that restrict analyses to certain theories. As such, even though it is hard to test hypotheses based on only observational data, it may be a good starting point from which to develop new theories that can help explain newly emerged behavioural dynamics. Human movement science initially controlled movement in situ, by isolating (presumed) individually controlled components, until the development of the idea of representative design (Araújo et al., 2007; Brunswik, 1955b; Davids, Button, Araújo, Renshaw, & Hristovski, 2006; Dhami et al., 2004; Dicks et al., 2009; Pinder et al., 2011; Vilar, Araújo, Davids, & Renshaw, 2012). Subsequently, movement science has developed many theories based on the analysis of movement responses, isolating only the mechanics. Whilst doing so, it has purposefully set aside many other aspects of human behaviour that cannot all be controlled simultaneously. For example, social interactions or psychological stressors may be of importance for how dynamics emerge through interacting individuals. By adopting a big data approach all of these components of interpersonal coordination are included without bias. Such analyses do however seem limited to statistical likelihoods of factors such as game outcome, rather than accurately predicting long-term human behaviour.

5.4 Major contributions and implications

5.4.1 Getting in time takes time

One of the more unexpected findings of this thesis is that a temporal advantage may be gained from local motion information the longer followers could observe the leader. In the first study (Chapter 2) it became apparent that the response time to the initiation of the movement was significantly smaller when presented with isolated global motion information. However, as the trial progressed, a clear temporal advantage was gained from being exposed to local as well as global motion information. It implies that when aiming to fully exploit the information
available, looking at another person for longer leads to better attunement to local motion information (cf., Fajen & Devaney, 2006). In the third study (Chapter 4) a similar effect was observed. In this study, response times were significantly faster when segmental motion information was available, but no difference was found for the relative phase. This implies that the turnaround points that were responded to fastest occurred when the movement cycle was longest, hence reducing the effect of the faster responses on the relative phase (as the magnitude of the discrete phasing is dependent on both the lag and the length of the current movement cycle). It can therefore be argued that observing another person for longer provides more cues about upcoming action. Whether this is sensitive to deceptive exploitation in competitive settings has not been studied.

5.4.2 Distance regulation

The perception-action coupling as described for interceptive actions based on global variables has been found transferrable to keeping-distance, a special case of distance regulation. This was found for both back-and-forwards as lateral distance keeping. Additionally, specifying information can be obtained from local sources of information. It was shown that a temporal advantage was gained when local information was available. Results also consistently showed that the temporal advantage may not always contribute towards the task-goal (i.e., keeping distance). Most notably, the added value of more local information sources became apparent when the leader was more irregular. Together these findings indicate that there may be an optimal balance between global and local information, as both have been shown pertinent for action in specific situations. It is up to the actor to skilfully decide which type of information to attune to. Negotiating these types of information and their associated temporal or spatial advantage may be entailed in skilful interacting.

5.4.3 Conclusion

The thesis aimed to examine skilful interacting in regulating distance, a fundamental aspect of interpersonal coordination. In three experiments it was shown that humans can effectively regulate distance with a range of information sources in a variety of tasks. It was repeatedly observed that visual angle information provided pertinent information for maintaining spatial accuracy. Segmental motion information (i.e., limb movements) on the other hand was shown to provide an advantage for tightening the temporal synchrony. Whilst acknowledging the
complexity of interpersonal coordination, it can be argued that keeping distance requires adopting flexible perception-action strategies. Skilful interacting – or interact-ability – may thus comprise of effectively attuning to pertinent sources of information, whilst avoiding becoming susceptible to deceptive movements.


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