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DYNAMICS OF ACQUIRING ADAPTIVE SKILLS IN A COMPLEX MULTI-ARTICULAR TASK: CONSTRAINTS ON META-STABLE ACTIONS

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Representative learning design

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Transfer of skill

Statement of Original Authorship

The work contained in this joint PhD thesis undertaken between QUT and the University of Rouen has not been previously submitted to meet requirements for an award at these or any other higher education institutions. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

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Abstract

This thesis, based on key ideas in ecological dynamics, presents data supporting a re-definition of the concept of learning and transfer of skills, using climbing as the research vehicle. The research programme sought to determine how environment-performance relationships support the acquisition of multi-articular skills, attempting to identify mechanisms that support improved transfer of learning due to practice. Specifically, these were learning contexts that induced behavioural meta-stability (a coexistence of stable and unstable coordination tendencies, and consequently promoted exploration of different motor behaviours), a mechanism through which individuals may exploit existing skills to also explore new, potentially more effective coordination modes. The programme of work addressed by this thesis was: (1) how skill was related to the exploration of behavioural opportunities (affordances) during performance; (2) how movement variability was related to performance during practice, and; (3) the underpinning role of exploration in supporting the transfer of learning. A pre- and post-test intervention design used a scanning procedure to determine the effect of practice on the stability of different climbing patterns of coordination. A group of beginners were shown to transition toward advanced styles of climbing and their performance on a transfer test revealed comparable levels of movement pattern stability to that of a more experienced group. Better climbing fluency in unfamiliar routes was related to increased exploratory behaviour during training conditions. In early practice, exploratory behaviour was associated with poor performance. After practice, increased exploration under transfer conditions was associated with better performance. The research evidence in this thesis suggests that, in complex multi-articular skills, exploration is a key mechanism for acquiring new skills and can support skills transfer. Extended practice under constraints that induce meta-stability were also shown to facilitate the acquisition of new coordination patterns. The programme of work provides evidence of key theoretical ideas, including affordances, degeneracy and meta-stability for underpinning the intervention and assessment of skill acquisition in physical activity and sport performance contexts.

Notre travail, prenant pour cadre la théorie écologique appliquée aux systèmes dynamiques, plaide en faveur d'une redéfinition du concept d'apprentissage des coordinations motrices. En prenant comme support la pratique de l'escalade, nous avons tenté de déterminer la place prise par l'interaction environnement-performance sur l'acquisition de compétences motrices en identifiant les mécanismes à l'origine de l'apprentissage. Pour cela, nous avons mis en place différents contextes d'apprentissage qui induisent un régime de métastabilité, mécanisme à travers lequel l'individu exploite des compétences acquises pour en développer de nouvelles. Des mesures ont donc été faites pour déterminer les effets de l'entraînement en escalade sur la stabilité des patterns de coordination. Après entraînement, notre analyse montre qu'un groupe de débutant adopte des coordinations motrices semblables à un groupe plus expérimenté en escalade. Des mouvements plus fluides dans des voies inconnues ont en effet été observés, un phénomène étroitement lié à une hausse du comportement exploratoire au cours des séances d'entraînement. Au cours de ces premières séances, le comportement exploratoire était corrélé avec une mauvaise performance. Après l'entraînement, une augmentation des comportements exploratoires est constatée lorsque le débutant est invité à découvrir une nouvelle voie, ce phénomène étant cette fois ci étroitement lié à une hausse de la performance. Nous mettons ainsi en avant que l'exploration joue un rôle clé sur le développement de nouvelles compétences motrices, ce qui accrédite le concept de transfert de compétences. Ce travail de thèse va donc dans le sens des concepts théoriques clés de la théorie écologique tels que l'affordance, la dégénérescence, la métastabilité pour mettre en place des situations d'apprentissages.

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CHAPTER 1. INTRODUCTION

Clarifying objectives

Table 1-1. Chapter 1 Table of contents.

1.1 Background

1.1.1 The role of variability in motor skill

There is an emerging scientific consensus that movement variability is functional and necessary for skilled performance (Bernstein, 1967; Davids, Glazier, Araújo, & Bartlett, 2003; Riley & Turvey, 2002), learning (Chow, Davids, Hristovski, Araújo, & Passos, 2011) and transfer (Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009). The topic of movement variability has been a subject of deep interest in motor control and learning, playing a central role in supporting key functions during performance such as environmental adaptation, injury risk reduction and facilitating change in coordination patterns (Davids et al., 2003).

Bernstein (1967) articulated that an important source of movement system variability is in how redundancy is managed when bringing the different parts of the movement system into a proper relation (i.e., its' coordination and regulation (Sporns & Edelman, 1993)). Bernstein defined redundancy as: 'more than one motor signal can lead to the same trajectory of a given motor system; moreover identical motor signals can lead to different movements under non-identical initial conditions or in the presence of variations in the external force field' (Sporns & Edelman, 1993, p. 961). More recently, these ideas have been further clarified in terms of degeneracy, pluripotentiality and redundancy. Degeneracy referring to non-identical structures recruited for a similar task (Edelman & Gally, 2001; Tononi, Sporns, & Edelman, 1999). Pluripotentiality indicating a structure being recruited for a selection of non-identical tasks (Friston & Price, 2003; Noppeney, Friston, & Price, 2004). And, redundancy referring to identical structures, recruited for the same task (clarified in (Mason, 2010, 2014; Mason, Winter, & Grignolio, 2015).

According to Edelman and Gally (2001), degeneracy and redundancy properties are exploited to dissipate constraining sources of energy coming into the system that might otherwise perturb it. Thus, movement variability, emerges from how neurobiological degeneracy and redundancy is coordinated (Tononi et al., 1999). This process, explained by self-organisation principles (Schöner & Kelso, 1988; Sumpter, 2006), results in the movement system forming temporary functional synergies by grouping muscles and joints to act in a unified manner (Kelso, 2012; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984). In this manner, the movement system can be coordinated without direct control of each potential degree of freedom (i.e. the multiple linkages, joints and muscles (Turvey, 1990) and sufficient flexibility to support the transition across stable states and potentially new system states if needed (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003).

Self-organisation is constrained by a backdrop of existing intrinsically stable system states and potential coordination regimes (Kelso, 2012). Kelso (2012) outlined different coordination regimes that can be identified that include mono-stability (where a single pattern of movement coordination is stable), multi-stability (where two or more patterns of movement coordination are stable) and the meta-stable regime (that corresponds to transition regions). Meta-stable regions are far enough from equilibrium that there is the equi-potentiality of different states of organisation, allowing the system flexibility to differentiate into multiple states (Juarrero, 1999). Meta-stable behaviour can emerge on the basis that constraints are scaled to challenge the stability of the existing stable state to a point that breaks any existing symmetries (Kelso, 2008) and places the individual on the edge(s) of two or more viable states of stability (Warren, 2006). the significance of meta-stability in motor learning, is that it acts as the mechanism underpinning the emergence of new coordination states (Kelso, 2012).

Constraints, therefore, play a significant role in reducing the dimension of the perceptual-motor workspace, defined as that region of space within which the movement system can interact (Newell, 1996; Newell, Liu, & Mayer-Kress, 2003; Sporns & Edelman, 1993). Constraints refer to interacting factors that place boundaries on movement coordination and include the individual, the environment and the task (Davids et al., 2003; Newell, 1986). Affordances are an additional source of constraint on movement coordination (Riccio & Stoffregen, 1988). Affordances referring to behavioural opportunities that are perceived based on the informational relationship between the individual and environment (Gibson, 1979). The realization of affordances are reflected in actions such as qualitative states of coordination (e.g. crawling, walking, climbing (Warren, 2006)). For example, by modifying constraints, a (re)organization of the movement system (such as transitioning from a walking to a running gait (Farley & Taylor, 1991)) can reflect an adaptation to key informational variables to maintain speed.

1.1.2 Exploiting variability to improve skill

Movement variability is both functional and necessary because it supports adaptations in the individual in relationship to their environment during performance and throughout learning (Chow et al., 2011). An important implication of movement variability induced during practice is that a more extensive functional exploration of degeneracy during practice, might lead to improved resilience and transfer of skill (Chow et al., 2011; Friston & Price, 2003; Mason et al., 2015; Noppeney et al., 2004). Practitioners can exploit the organizational principles of the movement system by changing specific parameters that constrain coordination, helping to guide learners to explore how different organizational states and information-based relationships can support goal achievement (Chow et al., 2011), encouraging adaptations in close relationship to constraints present during practice (Kelso, 2008). Indeed, inducing variability during practice has been connected to improved retention the transfer of skills (Chow, 2013; Magill & Hall, 1990; Ranganathan & Newell, 2013; Schöllhorn et al., 2009).

Transfer of skill and learning occurs when training in one context affects the performance and learning in a subsequent context (Adams, 1987; Carroll, Riek, & Carson, 2001; Newell, 1996).Transfer effects are, therefore, valuable for facilitating physical activity performed between training and some other context such as an intended performance situation (Lopes, Rodrigues, Maia, & Malina, 2011; Rinne, Pasanen, Miilunpalo, & Mälkiä, 2010; Vandorpe et al., 2012). Intervention induced variability, such as in the order of practice of actions (Porter & Magill, 2010), instructing individuals to include randomised behaviour (Schöllhorn et al., 2006), and, increasing the number of practice conditions (Huet et al., 2011), have led to significantly better transfer effects compared to paradigms where an individual practices under fixed conditions. The mechanism that underpins transfer pertain the greater exploration of the perceptual-motor workspace supported by the intervention induced variability, possibility allowing the individual to locate more effective coordinative behaviours or information-movement relationships that support performance (Chow et al., 2011; Huet et al., 2011; Lin, Fisher, Winstein, Wu, & Gordon, 2008; Schöllhorn et al., 2009; Stoffregen, Bardy, Smart, & Pagulayan, 2003). An additional perspective is, that the need to adapt behaviour to performance contexts that induce variability is a property that is shared with transfer contexts (Araújo, Davids, & Hristovski, 2006). That is, constraints that induce movement variability are more representative of the transfer context. Therefore, for individuals aiming to transfer their experience to an intended context, a benefit may be derived from designs that simulate corresponding levels of variability in the practice constraints (Araújo, Davids, & Passos, 2007; Travassos, Duarte, Vilar, Davids, & Araújo, 2012)). Indeed, the ability to transfer learning is conveniently contrasted with the properties of expertise, where, a key finding in experts is the superior capacity to transfer their skills (Rosalie & Müller, 2012; Seifert, Button, & Davids, 2013). One reason for this, according to Seifert et al. (2013), is that expert practice environments are constrained extensively by variability, routinely requiring adaptive behaviour (see also, (Baker, Cote, & Abernethy, 2003; Phillips, Davids, Renshaw, & Portus, 2010)).

An approach grounded in complex systems theory for inducing functional movement variability during performance is to design tasks that position individuals into meta-stable regimes (Hristovski, Davids, & Araújo, 2006, 2009; Pinder, Davids, & Renshaw, 2012; Seifert et al., 2014; Seifert, Orth, Hérault, & Davids, 2013). Individuals can be positioned to perform under a meta-stable regime by manipulating constraints so as to create an overlap in different affordances for action (Hristovski, Davids, Araújo, & Button, 2006; Pinder et al., 2012). For example, Hristovski et al. (2006) observed constraints which scaled the distance of boxers to a punch bag during practice facilitated affordances to constrain the emergence of a rich range of hitting actions. These results showed that a feature of practice in a meta-stable regime is for different patterns of movement coordination to be explored spontaneously (Hristovski, Davids, Araújo, et al., 2006). Although the mechanism for inducing meta-stability appears to be conceptually understood, the utility of this system state during practice has not been tested. A candidate hypothesis, is, that meta-stability supports a more extensive goal-directed exploration of system degeneracy and pluripotentiality (Chow et al., 2011). That is, conditions that support function movement variability during practice should lead to the acquisition of new skills and improved transfer of skill (Chow et al., 2011).

1.2 Research Aim

The thesis aimed to determine how environment-performance relationships (specifically learning contexts that promote exploration of different actions) support learning and transfer of multi-articular skill and then, determine what mechanisms support improved transfer of learning due to practice.

The research questions addressed by this thesis are:

(1) What models and frameworks explain the acquisition of new skill in complex/emergent physical activity contexts? And, what are the research priorities in this field?

(2) What research vehicle and measurement strategies are viable to investigate the acquisition and transfer of complex multi-articular skill?

(3) Do data acquired in using the research vehicle support the theoretical framework adopted?

(4) What strategies can be developed to improve skill acquisition in physical activity settings?

1.3 Conceptual Basis for the Thesis

Movement variability is functional and necessary for skilled performance (Bernstein, 1967), learning (Chow et al., 2011) and transfer (Seifert, Button, et al., 2013). Research is needed to evaluate in the role of movement variability for facilitating the transfer of skill in the sorts of complex environments that individual's normally participate in (Araújo et al., 2007; Rosalie & Müller, 2012; Seifert, Wattebled, et al., 2013). This thesis evaluates key theoretical mechanisms for acquiring skill, using climbing as the research vehicle.

While effective design of practice constraints is widely regarded as an essential part of improving skill acquisition (Moy, Renshaw, & Davids, 2014), a number of studies have highlighted important challenges to address. Chiefly, despite significant advances in theoretical frameworks (Chow, 2013; Davids & Araújo, 2010; Kelso, 2012; Warren, 2006) and increased attention to the adaptive role of movement system variability (Barris, Farrow, & Davids, 2014; Dicks, Button, & Davids, 2010; Wilson, Simpson, Van Emmerik, & Hamill, 2008), the belief that skill acquisition can be underpinned by rehearsal of an idealised movement pattern remains pervasive (Brisson & Alain, 1996; Chow, 2013; Moy et al., 2014; Schöllhorn et al., 2009; Seifert, Button, et al., 2013). To date, few studies can be identified to have evaluated the role of movement system variability during practice tasks that simulate constraints on the acquisition of multi-articular skill in the sorts of physical activity contexts individuals normally seek to participate. Therefore, it is important to address this knowledge gap in how movement variability relates to the design of practice constraints and the acquisition and transfer of skill.

It may be difficult to grasp the functional role of movement variability because traditional theories of skill acquisition have emphasised the repetition of an ideal movement pattern (Ericsson, Krampe, & Tesch-Römer, 1993), such as of a particular relative phase between limb segments (e.g., Schöner, Zanone, & Kelso, 1992). In contrast, many studies have found associations between the complexity of constraints and movement variability (Dicks et al., 2010; Mann, Williams, Ward, & Janelle, 2007; Orth, Davids, Araújo, Renshaw, & Passos, 2014; Pinder, Davids, Renshaw, & Araújo, 2011; Travassos et al., 2013; Travassos et al., 2012) and more research is needed to understand the role of complexity of constraints during skill acquisition (Newell, 1986; Wulf & Shea, 2002). Currently, continuous cyclical (Hong & Newell, 2006; Nourrit-Lucas, Tossa, Zélic, & Delignières, 2014; Nourrit et al., 2003; Teulier & Delignières, 2007; Teulier, Nourrit, & Delignières, 2006) and discrete actions (Barris et al., 2014; Chow, Davids, Button, & Koh, 2008; Chow, Davids, Button, & Rein, 2008) have been used to evaluate movement variability during learning of multi-articular skill. However, understanding acquisition of multi-articular coordination involving a mixture of continuous, rhythmic movement with nested discrete multi-articular actions is a major challenge that needs to be addressed for understanding transfer of learning across many physical activities, and currently, there are no movement models to evaluate learning in such tasks. It is therefore important to develop a viable research vehicle for future programmes of work.

Previous studies have investigated the role of constraints that induce adaptive movement variability during performance in experienced individuals (Hristovski, Davids, Araújo, et al., 2006; Pinder et al., 2012), but movement variability, such as exploratory behaviour, may not be functional for experienced performers and constraints that induce exploration may be considered more relevant to inexperienced learners who still need to explore new patterns of coordination. Conversely, if learning can be shown in experienced individuals, then the importance of designing practice constraints that induce variability would warrant more extensive investigations. Even in inexperienced individuals faced with a new learning task, exploration can rapidly decrease to asymptote with practice (Chow, Davids, Button, & Koh, 2007; Cordier, Mendès-France, Pailhous, & Bolon, 1994). If learning opportunities resolve under constraints that induce a meta-stable regime this would confirm that pedagogical strategies need to adapt with improved performance.

Improving skill is a central motivation for why individuals participate in physical activity and naturally, individuals engage in additional training activities intending to transfer learning across different contexts (Carroll et al., 2001). And yet, the learning behaviour of individuals under complex multi-articular tasks that individual seek to participate is poorly understood (Chow, 2013). The effective design of learning tasks should be informed by data that can characterise what learning behaviour under representative constraints resembles and, that can provide clear evidence after practice, participants can perform in a manner corresponding to individuals who have ‘naturally’ acquired their skill. The overall conceptual framework for this thesis is summarised in Figure 1.1.

Movement system variability

↓

The role of variability in skill

↓

Exploiting variability to improve skill

↓

Aim — **To explore research priorities**

Chapter 2: Acquiring functional movement variability: a literature review

Emphasis — ***Theoretical rational for understanding transfer of skill***

To develop a research vehicle

Chapter 3: Coordination in climbing: a literature review

A physical activity requiring transfer of skill

To develop methods

Chapter 4: Fluency in skilled climbers: a literature review

Developing techniques for measuring skilled coordination

To confirm theoretical model

Chapter 5: Constraints representing a meta-stable regime in a complex multi-articular task

- Effect of practice
- Effect of skill level

To evaluate mechanisms

Chapter 6 Skill its acquisition and transfer in a physical activity setting

- Effect of existing skill
- Acquisition of new skill

To identify implementation strategies

Chapter 7: Strategies for skill acquisition in climbing

- Develop strategies for implementing results in applied contexts

Figure 1-1. Conceptual framework for the thesis.

1.4 Thesis Outline

This thesis is presented in publication style. As such, each body chapter is designed to stand alone. In Chapter 2 through literature review I establish a perspective on how skill can be conceptualized as an emergent property that involves an exploration of the systems inherent degeneracy. Two theoretical themes emerged in relationship to the design of research tasks and the occurrence of functional movement variability that may support skill acquisition and its transfer. Firstly, referred to as representative design, it was found that the greater extent to which a task simulates properties of complex performance contexts, the more functional movement variability (including; co-adaptation, changes in coordination patterns and exploratory behaviour), is emphasised in study findings. Secondly, referred to as meta-stable behaviour, when required to perform under constraints that support multiple actions individuals tend to spontaneously explore a greater variety of qualitatively different patterns of action within- and between-trials of performance. Coincidently, research concerned with learning new skills also emphasises the role of spontaneous exploratory behaviour as a key indication that an individual can learn to coordinate new and better individual-environment relationships for improving performance. However, a very limited number of studies could be identified to have tested the role of functional movement in transfer contexts representative of a physical activity setting or skill. Research is needed to strengthen current theoretical frameworks by considering representative design, meta-stability and functional movement variability with respect to how these ideas can support learning and the transfer of skill. I propose therefore, that high priorities should be placed on research that can sample motor learning and transfer in complex physical activity and sport environments with active communities of expert participants.

In Chapters 3 and 4 I address the concern that most previous motor learning studies have been designed to test movement coordination in discrete interceptive tasks or in cyclical continuous tasks. I argue that participation in many physical activities pertains to tasks that nest cyclical locomotor behaviour with a rich mixture of discrete actions. In addition to this concern is that the transfer of skill within and across different domains of practice is lacking in empirical evidence. Hence, a research vehicle where individuals' use both locomotion and discrete actions and that can evaluate questions pertaining to transfer would be of considerable value. I therefore propose the physical activity of climbing can provide a new research vehicle to address these concerns. In Chapter 3 I undertake a much needed systematic review of the literature examining in detail the impact of constraints on coordination of action during performance, and effects of skill, practice and constraints manipulation in climbing. It is found that further research is needed to understand the impact of different intervention conditions on learning and to evaluate individuals with different levels of experience to determine what skills require climbing specific experience. In Chapter 4 I review the strengths and limitations of existing methods to measure skill in climbing. I conclude that measures require both spatial-temporal indicators of fluency alongside estimates of the climber's intentions by capturing performatory and exploratory behaviour.

In Chapter 5 I determine that previous studies showing meta-stability in complex multi-articular tasks have used experienced individuals and have not reported trial effects. I argue that if learning is induced in experienced individuals, observation of behaviour over repeated trials of practice is needed to confirm this. Furthermore, if the coordination variability induced under a meta-stable regime can support transfer, multiple conditions need to be evaluated. In addition, I determine that it is also unclear how inexperienced individuals respond to being located in a meta-stable region during practice. Therefore, I proposed an experiment that observed the practice of a group of experienced and a group of inexperienced climbers under meta-stable task conditions and also, the transfer of their performance. I conducted an analysis of their exploratory behaviour at the hip and hand levels using a semi-automatic tracking procedure combined with manual annotations. This study showed that learning emerged at different levels, the hands and body. The amount and rate at which learning occurred was shown to interact with the amount of previous climbing experience reported by the participants. More experienced climbers transferred learning that was induced under the meta-stable condition. Inexperienced climbers were induced to learn on a route that required use of an advance climbing action and the meta-stable route. Under transfer, the individuals in the inexperienced group who showed more exploration performed best.

In Chapter 6, through a three part experiment, I considered the impact of prolonged practice under meta-stable task design. I was primarily concerned with confirming existing models of skill acquisition in the complex multi-articular case. Related to this concern was whether such a protocol, which followed traditional design principles of extended practice under the same constraints, would lead to the acquisition of behaviour representative of skills that experienced indoor climbers' exhibit. In **Experiment 1** I therefore first determined how prior experiences influence the behavioural tendencies of individuals under meta-stable climbing constraints and whether the grasping pattern used, related to climbing performance. I observed three groups, a group of experienced climbers, a group of professional firefighters, and a group of beginners climb on a route they had never physically practiced. In this study I combined manual annotation of grasping actions with automatic tracking of hip position using a basic Kalman filter. It was found that the firefighters, when given the choice, tended to use overhand grasping as opposed to a pinch grip, and significantly more so than both experienced climbers and beginners. However, the performance of firefighters was not better than the beginners. This suggesting that whilst a variety of ways of completing the route were possible, the behaviour at the hand level did not drive the smoothness of the climbing trajectory and that intrinsic dynamics were a significant constraint on the coordination of action.

In **Experiment 2** I therefore developed a method to evaluate the ability of beginners to use different climbing patterns of coordination. I did this by adapting a scanning procedure, which required participants to attempt to use different patterns of climbing coordination. In this study I applied automatic tracking of hip position synchronised with a worn sensor attached the hips and climbing wall to determine the coordinated body-wall angle. The results showed that both advanced climbers and beginners could adapt to the task constraints, albeit, with poorer performance. The beginners who fell, however, were unable to move at the same time as being orientated with the side of the body with respect to the wall.

In **Experiment 3** a pre- and post-test intervention design used the scanning procedure and additional transfer tests to show the effect of practice on the emergence of different climbing patterns of coordination in a group of beginners. A group of beginners were shown to transition toward advanced styles of climbing and performance on a transfer test revealed comparable levels of performance to a more experienced group. This study showed that extensive practice under meta-stable task design can lead to behaviour similar to experienced climbers, however the same degree of flexibility was not evident. Additionally, it was found that the learning dynamics were individually specific. Whilst globally, performance improvement followed a linear function, some individuals showed a linear improvement whilst other showed evidence of an abrupt transition.

In Chapter 7 I discuss the research evidence in this thesis, suggesting that in complex multi-articular skills, exploration is a key mechanism for acquiring new skills and can support fluent performance under transfer conditions. The data suggest that representing meta-stability in practice constraints supports the capacity to adapt performance to the inherent variability found in physical activity settings such as the climbing domain. I discuss the impact of these ideas, underpinned by theoretical frame-works grounded in ecological psychology and dynamical systems theory, through practical strategies in how route design (such as hold orientation and grasp-ability) can be used to establish representative tasks for acquiring climbing specific skill through promoting exploration in a manner consistent with the overall aim of improvement in performance over-time.

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CHAPTER 2. REVIEW PAPER 1: THEORETICAL FRAMEWORK

Acquiring functional movement variability for performance and transfer in physical activities and sport

Table 2-1. Chapter 2 Table of contents.

Table 2-2. Chapter 2 Key points.

- Rather than be considered as error, movement variability should also be evaluated in how it can be functional to enhance performance in complex multi-articular skills.
- Functional movement variability in complex multi-articular tasks is indicated by qualitative changes in movement patterns, co-adaptation amongst different components of the movement system, and exploratory behaviour.
- Novel skill learning involves exploratory behaviour that can be facilitated through constraints manipulation that also allow individuals to use existing skills: the adaptation of existing skills is one reason that Individuals, faced with the same learning task, differ in the rate and nature of learning.
- Whilst in simple tasks, destabilization of pre-existing skills and reorganisation of the entire repertoire have been demonstrated, the nature of learning in complex multi-articular physical activity contexts in poorly understood.
- Intervention induced variability (changing the order that skills are practice, increasing the number of different practice conditions, requiring random use of different actions) can improve the transfer of skill after practice.

Abstract

How to effectively design practice contexts that can improve performance in developing experts is an important issue and inevitably must be addressed at the level of the learner and their practice constraints. There are different views on how to enhance expertise in complex multi-articular tasks through training. There is however, an emerging scientific consensus that developing experts, being exposed to functional movement variability (FMV) during practice promotes good retention (the ability to reproduce a skill under the same conditions, usually after a delay) and transfer of skill and learning (better performance and learning in intended contexts, such as a new environment, due to experience under training conditions). This chapter provides an overview of how practice contexts that induce FMV are designed and why these designs might facilitate the transfer of skill and learning. An integrative review was conducted and retrieved published literature that: a) evaluated constraints to induce FMV during learning in complex multi-articular tasks, and; b) evaluated the effect of interventions on the retention and/or transfer of skill in full body multi-articular contexts. Results show that FMV (co-adaptive behaviour, changes in coordination patterns, and exploration) during practice can be induced through specific arrangements of constraints, including: task novelty, instructions and constraints manipulation in the environment. The most straightforward explanation for the transfer of skill between different performance contexts is that arrangements of constraints on behaviour during practice represent similar arrangements of constraints under transfer conditions, and include the emergent, unpredictable, properties of constraints. However, there are challenges in providing clear design strategies for inducing FMV during learning that arise from uncertainties regarding: a) the characteristics of learning behaviour that leads to transfer and; b) determining whether learning has resulted in a capacity to perform in a manner corresponding to experts who ‘naturally’ (without scientific intervention) have acquired their skill. Providing clear guidelines on constraints manipulation during learning are reliant on developing research strategies that address these gaps. It is proposed, therefore, that high priority be placed on research that can sample performance, learning and its transfer under constraints representative of the complex environments that individuals normally participate and with an active community of experts.

2.1 Introduction: The importance of functional movement variability in skilled behaviour

Improving skill is a central motivation for why individuals participate in complex physical activity settings (Allender, Cowburn, & Foster, 2006; Ntoumanis, 2001; Stodden et al., 2008), and naturally, individuals engage in additional training activities intending to transfer skills across different contexts (Carroll, Riek, & Carson, 2001), such as using skills acquired from practice in training sessions for performance in competitive situations (Pinder, Renshaw, & Davids, 2013). Whilst there are different perspectives on skill learning, there is an emerging scientific consensus that functional movement variability is necessary for skilled performance (Bernstein, 1967; Davids, Glazier, Araújo, & Bartlett, 2003; Riley & Turvey, 2002), learning (Chow, Davids, Hristovski, Araújo, & Passos, 2011) and transfer (Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009). Specifically, movement variability can be functional on the basis that it supports goal achievement during performance and learning through environmental adaptation, reduced injury risk and change in coordination patterns (Bartlett, Wheat, & Robins, 2007; Davids et al., 2003). The importance of being exposed to functional movement variability (FMV) in learning contexts has been highlighted in recent reviews on: expert performance (Headrick, Renshaw, Davids, Pinder, & Araújo, 2015; Seifert, Button, & Davids, 2013); talent identification and development (E. Phillips, Davids, Renshaw, & Portus, 2010; Suppiah, Low, & Chia, 2015); novel skill learning (Chow et al., 2011); infant development (Deutsch & Newell, 2005; Dusing & Harbourne, 2010; Hadders-Algra, 2010; Piek, 2002; Vereijken, 2010), rehabilitation (Harbourne & Stergiou, 2009; Stergiou, Harbourne, & Cavanaugh, 2006; Wu & Latash, 2014), health (Srinivasan & Mathiassen, 2012), and; during skills practice across a range of ability levels (Chow, 2013; Davids, Araújo, Correia, & Vilar, 2013; Preatoni et al., 2013; Schöllhorn et al., 2009). And yet, observational data on the functional role of movement variability of individuals in learning complex multi-articular tasks that resemble physical activity or sport contexts remains particularly scarce (Chow, 2013; Rosalie & Müller, 2012).

While theoretically grounded design of practice constraints is regarded as an essential part of improving skill acquisition (Chow, 2013; Lai et al., 2014; McKenzie, Alcaraz, Sallis, & Faucette, 1998; Moy, Renshaw, & Davids, 2014), a number of studies have highlighted important challenges to address (Davids, Renshaw, & Glazier, 2005; Mann, Williams, Ward, & Janelle, 2007; Travassos et al., 2013). Of major concern is, that, despite advances in theoretical frameworks for explaining skilled behaviour (Chow et al., 2011; Davids & Araújo, 2010; Kelso, 2012; Warren, 2006) and increased attention on the functional role of movement variability (Barris, Farrow, & Davids, 2014; Dicks, Button, & Davids, 2010; Wilson, Simpson, Van Emmerik, & Hamill, 2008), the belief that skill acquisition can be underpinned by rehearsal of an idealized movement pattern remains pervasive (Brisson & Alain, 1996; Chow, 2013; Davids, Araújo, Seifert, & Orth, 2015; Schöllhorn et al., 2009; Seifert, Button, et al., 2013). Traditionally, variability has been viewed as dysfunctional in that the individual is not able to organize behaviour corresponding to the presupposed, ideal state (Glazier & Davids, 2009). One reason that it may be difficult to grasp the functional role of movement variability is because traditional theories of skill acquisition have emphasized the repetition of an ideal movement pattern under fixed conditions, such as of a particular relative phase between limb segments (e.g., Schöner & Kelso, 1988), the speed and accuracy of repetitive finger tapping (Hick, 1952) or required periodic movements between people (Schmidt, Carello, & Turvey, 1990). In contrast, studies operationalizing complex system frameworks have found associations between the complexity of the performance setting and behavioural variability functional for goal achievement (Dicks et al., 2010; Fujii, Yamashita, Kimura, Isaka, & Kouzaki, 2015; Orth, Davids, Araújo, Renshaw, & Passos, 2014; Pinder, Davids, Renshaw, & Araújo, 2011a; Pluijms, Cañal-Bruland, Hoozemans, & Savelsbergh, 2015; Travassos, Duarte, Vilar, Davids, & Araújo, 2012). An important limitation that needs to be addressed in experimental design is that reductionist approaches can lead to an emphasis on the invariant features of skilled behaviour and performance environments, ignoring the role that variability in these factors may play in goal achievement (Button, Seifert, O'Donivan, & Davids, 2014).

The purpose of this chapter was therefore to evaluate how practice contexts that induce FMV are designed and why these designs might facilitate the transfer of skill and learning in complex multi-articular tasks. *Transfer of skill* refers to when experience in one context affects the performance in a subsequent, often intended, context (Carroll et al., 2001; Davids et al., 2015; Newell, 1996). *Transfer of learning* referring to when experience in one context affects the learning (such as its rate or dynamics (Newell, Liu, & Mayer-Kress, 2001)) in a another practice context (Issurin, 2013). Understandably, individuals seek to achieve *positive transfer*, which refers to improvements in performance or learning by practice in training contexts different from the intended context (Carroll et al., 2001; Issurin, 2013; Rosalie & Müller, 2012)). Additionally, individuals seek to avoid *negative transfer* (reduced performance or learning) or *neutral transfer* (an absence of significant change in performance or learning) (Issurin, 2013). More specially then, the aim of this integrative review was to evaluate the role of functional movement variability in underpinning positive transfer effects.

The review is structured in four parts, in the first part, a framework is developed where FMV is more thoroughly defined and sources of FMV are discussed with respects to the organisational principles of the movement system. The second part considers the impact of experimental design on FMV, aiming to detail how movement variability can be influenced by contextual features of performance and practice contexts. The third part summarises approaches to inducing adaptive variability, attempting to integrate the key design principles for acquiring FMV. The fourth section discusses implications that arise from the review focussing on the proposed mechanisms underpinning why inducing FMV during practice promotes transfer of skill. Guidelines are also provided aimed at assisting individuals to transfer skilled behaviour and/or learning to an intended environment and for summarising identified research priorities.

2.2 Movement variability and goal achievement

2.2.1 Adaptive variability reflects the organizational principles of coordinated behaviour

Bernstein (1967) articulated that an important source of movement variability was in how redundancy is managed when bringing the different parts of the movement system into a proper relation (i.e. its' coordination and regulation (Sporns & Edelman, 1993)). Bernstein defined redundancy as: 'more than one motor signal can lead to the same trajectory of a given motor system; moreover identical motor signals can lead to different movements under non-identical initial conditions or in the presence of variations in the external force field' (cited in Sporns & Edelman, 1993, p. 961). More recently, these two ideas have been defined as *degeneracy* (non-identical structures recruited for a similar task, or a many-to-one functionality (Edelman & Gally, 2001; Tononi, Sporns, & Edelman, 1999)) and *pluripotentiality* (a structure being recruited for a selection of non-identical tasks, or a one-to-many functionality (Friston & Price, 2003; Noppeney, Friston, & Price, 2004)) respectively. With *redundancy* more specifically defined as identical structures, recruited for the same task (Mason, 2010, 2014; Mason, Winter, & Grignolio, 2015). These ideas are clarified in Figure 2.1 using the example of how an individual might use climbing holds in various ways. The left panel exemplifies redundancy in how fingers as identical structures might be used for the same action of horizontally grasping a climbing hold. The middle panel exemplifies degeneracy, showing how different parts of the movement system, either the left hand, right hand or left foot, can be used to horizontally grasp a hold. Finally, pluripotentiality is exemplified with the left hand being used to grasp a climbing hold horizontally, vertically and diagonally. Degeneracy in rock climbing can be further extended to different levels of analysis by considering the large range of hand grasping patterns and body positions regularly used to achieve a specific hold (K. C. Phillips, Sassaman, & Smoliga, 2012) and the possibility of different patterns of inter-limb coordination. For example in ice climbing, recent studies have revealed that climbers exhibit several stable patterns of motor coordination (e.g., horizontal-, diagonally-, vertically- and crossed-located angular positions of the ice tools and shoe spikes, (Seifert, Coeurjolly, Hérault, Wattebled, & Davids, 2013)).

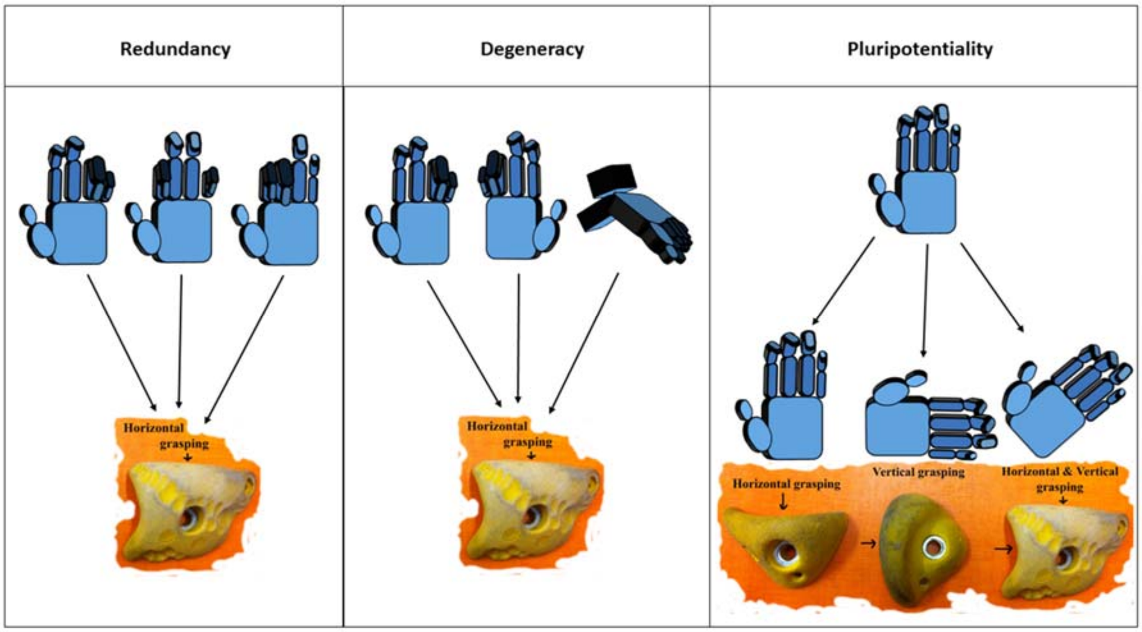

Figure 2-1. Redundancy, degeneracy and pluripotentiality defined.

Bernstein's ideas collectively, have invited researchers to consider that skill level can be associated with *increasing* movement variability, both at the within individual and between individual levels, as a function of how *degrees of freedom* (the multiple linkages, joints and muscles (Turvey, 1990)) are explored and released in relationship to the constraints available during the coordination of behaviour (Button, Macleod, Sanders, & Coleman, 2003). Hence, functional movement variability is understood by considering how movement variability supports achieving a contextual goal. FMV can be measured in two broad respects, on the basis of quantitative (standard deviation, entropy) and qualitative (phase transition, intermittency phenomena) approaches (Davids, Hristovski, et al., 2014). In taking a complex systems approach, FMV, emerges during performance from how neurobiological degeneracy and redundancy is coordinated on an individual basis, forming a starting point for measurement. According to Edelman and Gally (2001), degeneracy and redundancy properties are exploited to dissipate constraining sources of energy coming into a system that might otherwise perturb it and which can potentially increase the complexity of the system. This process relies on *self-organisation* principles (Schöner & Kelso, 1988; Sumpter, 2006) and results in the formation of temporary functional synergies, such as groupings of muscles and joints to act in a unified manner (Kelso, 2012; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984). In these respects, the movement system can be coordinated without a direct control of each movement degree of freedom, allowing the flexibility for individuals to transition across stable states and potentially new system states if needed (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003). A characteristic feature of complex adaptive systems is the transition in an *order parameter* (a collective variable that describes the overall state of the system) as a non-linear consequence of scaling a control parameter (Kelso, 2012). Where the *control parameter* is a property (such as ground speed during locomotion) that moves the system through different parts of the state space as captured by the order parameter (such as the phase relationship between limbs during locomotion describing a walking or running gait (Jordan, Challis, & Newell, 2007)). The control parameter does not determine the systems behaviour; instead, a *phase transition* and the subsequent (re)organization are said to emerge spontaneously because of broken symmetry (Kostrubiec, Zanone, Fuchs, & Kelso, 2012). In other words, fluctuations from within the system that provide the mechanism facilitating a transition to a new state as the system becomes increasingly unstable (Kelso, 2012).

Coordination tendencies, such as particular movement patterns, are constrained by a backdrop of an individual's existing intrinsically stable system states and potential coordination regimes (Kelso, 2012; Kostrubiec et al., 2012). Kelso (1984) first operationalized the concept of coordination regimes in understanding the organization of behaviour using a bimanual coordination experiment. Specifically, participants were asked to oscillate their index fingers at the same speed (cycling frequency) with variations in the spatial relationship with each trial. Across all phase modes possible, two were performed with stability without requiring practice, in-phase and anti-phase. In-phase and anti-phase coordination corresponding to synchronized motion of the fingers in the same or opposite direction respectively (Kelso, 1984). Emergent coordination patterns (those occurring spontaneously) represent stable states or attractors. *Attracters* refer to patterns in which the system remains most often over time, to which the system returns to after perturbation, and to which the system settles after a transition (Kostrubiec et al., 2012; Schöner & Kelso, 1988). Kelso (2012) outlined different coordination regimes that can influence the attracters available to an individual and that include *mono-stability* (where only a single pattern of movement coordination is stable), *multi-stability* (where two or more patterns of movement coordination are stable) and the meta-stable regime.

Specifically, meta-stable regions are far enough from equilibrium that there is the equi-potentiality of different states of organisation, allowing the system flexibility to differentiate into multiple states (Juarrero, 1999). *Meta-stability* refers to a coexistence of integration tendencies (meaning component couplings, such as two limb pairs, are stable) and segregating tendencies (meaning component couplings are unstable). Coexisting integration and segregation tendencies result in an intermittency between difference coordination tendencies allowing functional performance under conditions of broken symmetry, albeit, with the presence of brief periods of instability (Palut & Zanone, 2005). Also referred to as a regime of 'relative coordination', 'intermittency' or 'loss of entrainment' (e.g., (Kostrubiec et al., 2012)), meta-stability, has operationally been identified in behavioural terms by considering movement variability at the within (Pinder, Davids, & Renshaw, 2012) and between (Hristovski, Davids, Araújo, & Button, 2006) trial levels. Within trials, behavioural meta-stability may be identifiable when multiple transitions between states occurs (Palut & Zanone, 2005), and between trials when an equi-potentiality of behavioural states is observed (Hristovski, Davids, Araújo, et al., 2006; Pinder et al., 2012). Consequently the meta-stable regime may promote functional movement variability in the form of exploration of different motor behaviours with a direct relationship to satisfying constraints on performance.

In practice, system tendencies can be facilitated on the basis of parametric control and according to Kelso (2012), requires identifying important interactions amongst key constraints that can lead the system toward different coordination regimes such as through a phase transition. *Constraints* refer to interacting factors that place boundaries on movement coordination and include the individual, the environment and the task (Davids et al., 2003; Newell, 1986). Affordances are an additional source of constraint on movement coordination (Riccio & Stoffregen, 1988). *Affordances* refer to behavioural opportunities that are available to be perceived based on the informational relationship between the individual and environment (Gibson, 1979) whose pick-up is influenced by structural (e.g., limb size, (Warren, 1984)) and functional (e.g., running speed (Orth et al., 2014), movement patterns (Boschker & Bakker, 2002), skill (Rietveld & Kiverstein, 2014)) aspects of the individual relative to properties in the environment.

In experimental design, the researcher introduces objects, places and activities designed to influence the information-movement couplings that are used to locate and regulate affordances (Gibson, 1979). Thus behaviour may be more or less encouraged or inhibited, when constraints, such as certain equipment or environmental conditions make affordances more or less available for use. Because affordances invite ways of achieving behavioural goals (Withagen, de Poel, Araújo, & Pepping, 2012) they can be observed in the movement patterns that an individual explores and adopts. For example, when multiple affordances are made to overlap by manipulating constraints, a meta-stable regime of performance can be induced, making some affordances more functional to the individual (Hristovski, Davids, & Araújo, 2006, 2009; Pinder, Davids, & Renshaw, 2012). Constraints, therefore shape the landscape of affordances, influencing the likelihood of one accepted over another during performance (Warren, 2006). These ideas are summarized in Figure 2.2 below.

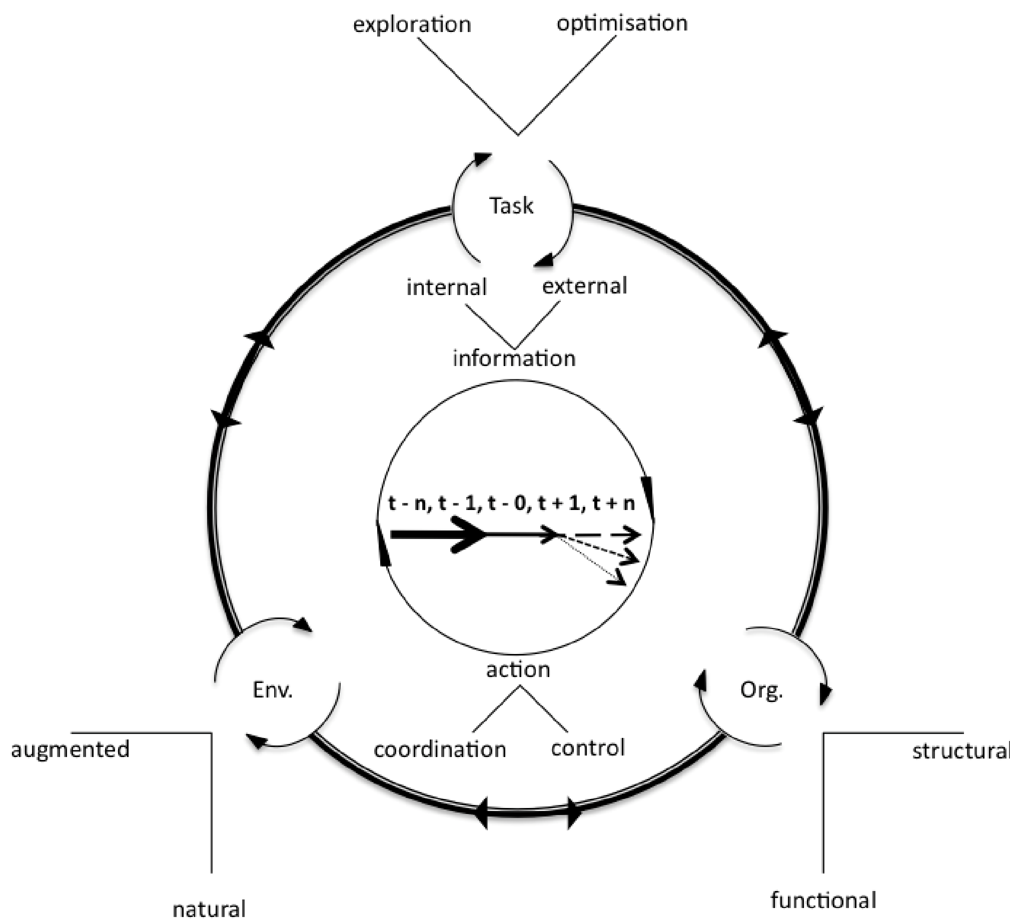

Figure 2-2. Interpretation of the constraints model integrated with the ecological approach to information and action. **Env**. = environment, **Org**. = Organism.

In Figure 2.2 a summary of complex systems frameworks discussed thus far is presented (and was adapted from many of the ideas in (Newell & Jordan, 2007)). The outer system of arrows indicate that the coordination system is bordered by constraints which are open to interaction in the form of informational or energy exchange. Note that outer boundary is made up of two lines, the thickest outer line represents long time scales, such as learning, and the thin inner line represents shorter timescales, such as performance (Newell et al., 2001). The inner system of information and action forms a closed loop indicating a co-dependent coupling between these two processes. Information coming from internal and external sources both influences and is created by actions that are understood in terms of their global pattern of coordination (qualitative behaviour such as walking or running), or parameters specific to the control of the movement (such as timing or positioning of limb segments) (Davids et al., 2003). Note also the capacity for the individual's behaviour to interact with the surrounding constraints. The progression of arrows within the information-action cycle represents the emergent evolution of behaviour over time. Multiple arrows with different weights are represented for future states because this allows for adaptation to changing circumstances and can represent multiple behavioural opportunities, some with greater likelihood to emerge than others. For instance, one affordance may become more or less expected to emerge based on likelihood of success or movement efficiency (Warren, 2006). The characteristics of constraints are also referred to in order that these properties be conceived of as modifiable for experimental and learning design (Davids et al., 2015). For example a coach might *augment* the environment by using artificial constraints such as different lights, or focus on improving an individual's structural characteristics through weight management. On the other hand, instructions might emphasise the individual focus on exploring new techniques or refining existing techniques.

In summarizing, the information used to constrain patterns of coordination has been related to the performer-environment relationship. Constraints and affordances both play a significant role in influencing the nature of movement variability, functional in how it supports the individual in meeting or enhancing task performance. FMV has also been argued as measurable at qualitative and quantitative levels. How constraints influence the functionality of movement variability, is developed in the following section by considering in more detail the influence of timescale, interacting constraints and perception action-coupling. These ideas are developed in the following section with the aim to provide a basis for appropriately designing experiments and learnings contexts for understanding adaptive behaviour in physical activity or sport related settings.

2.3 Experimental design of constraints and functional movement variability: The role of movement, the environment and performance context

Movement variability is functional on the basis that is supports performance with respect to changes in constraints, and the emergence of new behaviours that can improve performance (Bartlett et al., 2007; Davids et al., 2003; Seifert, Komar, et al., 2014). Performance is predicated on an individual's *adaptability*, referring to a balancing between stability and flexibly in behaviour (Seifert, Button, et al., 2013; Warren, 2006). *Stability* is a capacity to readily reproduce a movement pattern with a high degree of reliability (Warren, 2006). Movement patterns are stable in that the functional form of movement is consistent over time, resists perturbation and is reproducible on separate occasions (Warren, 2006). *Flexibility* is the ability to use alternative solutions in cases where other movement solutions are no longer feasible due to changes in the environment or individual (Ranganathan & Newell, 2013, p. 67; Seifert, Komar, et al., 2014). During performance, maintaining a balance of stability and flexibility supports *skilled performance* (the capacity to achieve an outcome with certainty and efficiency (Newell, 1991; Todorov & Jordan, 2002)).

It is widely accepted that the accurate coupling of movement to information in internal and external environments is the perceptual-motor basis that individuals achieve adaptability for skilled performance (Davids, Kingsbury, Bennett, & Handford, 2001; Smits, Pepping, & Hettinga, 2014). Referred to as *information–movement coupling*, this is an important principle in research task design (Davids et al., 2001; Handford, Davids, Bennett, & Button, 1997), with many convincing examples that perceptual capabilities can only be fully realized when examined in situations where naturally adapted couplings to action are available (Bootsma, 1989). The concern is that preventing an individual from moving during tasks or removing key environmental properties may arbitrarily cut individuals off from important sources of information, curtailing the use of adaptive movements that support performance (Bootsma, 1989; Dicks et al., 2010; Oudejans, Michaels, & Bakker, 1997).

2.3.1 Movement dependent sources of information

Movement dependent sources of information are not confined to the action(s) of any single limb, rather, the entire movement system and its interactions amongst its many degrees of freedom during an action can be important sources of information (Hoffman & Deffenbacher, 1993; Michaels, 2000). For example, when kicking a football for power and accuracy, a proximal to distal sequencing of inter-limb coordination emerges prior to foot-ball contact (Kellis & Katis, 2007). Referred to as *prospective control* (Montagne, Cornus, Glize, Quaine, & Laurent, 2000) movements throughout the entire action can be coupled to upcoming objects, events, surfaces and significant others. Taking the straightforward example of kicking, prospective control can be exemplified in, the initiation of hip rotation, coordinated with respect to the timing of upcoming events, such as knee extension of the kicking leg and the subsequent foot-ball contact (Kellis & Katis, 2007).

Co-adaptive and transitional behaviour are both functional forms of movement variability that emerge on the basis of movement dependent sources of information. For example in interpersonal and team based tasks, the interactions with a single or multiple individuals, requires that individuals balance a mixture of cooperative and competitive concerns (Duarte, Araújo, Correia, & Davids, 2012; Grehaigne, Bouthier, & David, 1997; Passos, Araújo, & Davids, 2013). In these activities, individuals coordinate behaviour against opponents and depending on the activity, can also seek to coordinate with team members to support a common competitive goal (McGarry, Anderson, Wallace, Hughes, & Franks, 2002). This requires attention to key task objects, such as a ball and field markings (Headrick et al., 2012), and an array of functionally differing team members and opponents (Bourbousson, Séve, & McGarry, 2010; Cordovil et al., 2009). McGarry et al. (2002) outlined how two teams or individuals can be understood as a coupled system that displays coordination tendencies where critical fluctuations can emerge when individual or team actions serve to destabilize or (re)stabilize the two teams of coordinating players. *Critical fluctuations* (challenges to the systems stability) might take the form of strategic maneuvers, such as a feint (Fujii et al., 2015), or positional readjustments to address an error made by a team-member and may require a complete reorganization of the established coordination state (Bourbousson, Seve, & McGarry, 2010).

For example, Palut and Zanone (2005), observed that in tennis match play a variety of different coordination regimes can emerge, such as lead-lag relationships in competitive dyads as well as the intermittency (or metastable) regime (see also, (McGarry, 2006)). According to Palut and Zanone (2005), these additional regimes highlight the key symmetry breaking role of strategic discrete actions that can abruptly emerge during periods of match play (see also (Yamamoto et al., 2013)). Accordingly, the co-adaptive behaviours through which an attacker or a defender influences the system stability can be considered an indication of the quality of performance (McGarry et al., 2002). Indeed during attack, the use of variability in behaviour has been previously highlighted as way of achieving a competitive advantage (Jäger & Schöllhorn, 2007, 2012). Consequently, not relying extensively on preconceived game plans during defense so that adaptation to emergent features of match play has been stressed for training design (Bourbousson, Seve, et al., 2010).

The importance of movement dependent sources of information is further emphasised in considering findings from experimental task designs that prevent individuals from functionally acting on information (Bootsma, 1989; Dicks et al., 2010; Oudejans et al., 1997). For example, through meta-analysis Travassos et al. (2013, p. 212) revealed that expert-novice differences were larger on measures of both: a) the time between an individual being presented with stimulus and the individuals response (their decision time), and; b) frequency at which a response was assessed as accurate (response accuracy), when requisite responses required the performance of functional actions. Specifically, Travassos et al. (2013) defined functional actions were where the task goal was attempted through an action as opposed to making verbal reports or micro-movements such as pressing a button.

2.3.2 Dynamic and noisy environmental properties improve skilled performance

Whilst, experimental or learning design can allow individuals to simulate or mimic a movement, that may lead to the conclusion that sufficient movement dependent sources of information are present, of additional concern is that experimental environments can fail to represent the nature and array of stimuli available for perception and action in an individual's natural performance or learning context (Araújo, Davids, & Passos, 2007; Papastergiou, 2009)}. According to Brunswik (1956), normally, individuals must cope dynamically with multiple, noisy, messy situations, which occur in the environment (cited in Araújo et al., 2007). Brunswik's arguments were based on the idea that human behaviour evolved from, and is adapted to, natural, chaotic performance environments that contain inherent uncertainty (Tolman & Brunswik, 1935), or as Brunswik (1955) described it, a 'semierratic ecology' (p. 209). In a similar fashion, physical activity and sport performance contexts, can require the co-adaption and transition across a variety of movement solutions during performance in response to dynamic changes in internal and external environments that cannot be predicted in advance of performance (Davids et al., 2015). For example, opponents can deceive and disguise their intentions through movement pattern variability and invariability in order to maximise uncertainty (Müller & Abernethy, 2012; Renshaw & Fairweather, 2000; Rowe, Horswill, Kronvall-Parkinson, Poulter, & McKenna, 2009).

Interceptive tasks are a good example of an activity that requires FMV, both in terms of co-adaptation and changes in coordination solutions in order to cope with the emergent demands of the environment. Interceptive tasks involve coordination between a participant's body, parts of the body or a held implement, and an object in the environment (Davids, Savelsbergh, & Bennett, 2002).

When under extreme time constraints, individuals develop strategies to exploit information available from events occurring before the object is even visible (referred to as anticipation skill). In physical activities and sports, the deceptive behaviour of opponents also means that, adaptive behaviour relative to object for interception during its flight, also imparts a considerable advantage for success (Müller & Abernethy, 2012).

For example, Pinder et al. (2012) examined the shot selection, movement kinematics and quality of performance in five experienced cricket batters, when facing balls delivered by bowlers to one of four possible, randomly determined, delivery lengths (bounce points). It was found that when balls were delivered at a short length (the ball bounced further away from the batters), the batters always used a striking action where they stepped toward the ball (termed a front-foot shot). When balls were delivered at a long length, the batters always stepped away from the ball prior to striking the ball (back-foot shot). When the ball was delivered at an intermediate length, the batters used both actions in an equi-probable manner across all performance trials without performance outcome decrement. Additionally, movement variability was observed in the timing of actions, and which according to the authors, when taken with respect to the consistent performance achievement, was functional for adapting to the uncertainty that such conditions impose. Specifically, according to Pinder et al. (2012), the changing constraints facilitated the perception of different behavioral opportunities, where the ball pitched at the intermediate distance reflected a metastable region of performance, whereas the short and long pitched deliveries constrained the emergence of mono-stability in batting behaviour, either as a front-foot or back-foot striking action respectively. See Figure 2.3 below for details.

Figure 2.3 shows how constraints can be manipulated to position an individual into a metastable performance regime as reflected in the impact on movement coordination. The top panel shows two qualitatively distinct ball striking patterns. The middle panel shows that the likelihood of a front-foot or back-foot shot emerging is influenced by scaling the delivery length of the ball to be intercepted. At a specific distance, either a front-foot shot or back-foot shot is shown to emerge with equal likelihoods. The bottom panel shows also the impact of performing in the meta-stable regime on the timing of key actions relative to the time of bat-ball contact. At the intermediate distance, a greater amount of variability is evident in the coordination of action with respect to the ball. From a practice design perspective the implications of scaling constraints in this fashion suggest that individuals naturally exhibit exploration when constraints encourage a meta-stable regime. In recalling the discussion regarding degeneracy for example (refer back to Figure 2.1), a meta-stable regime might facilitate the exploration of movement pattern degeneracy (Chow et al., 2011).

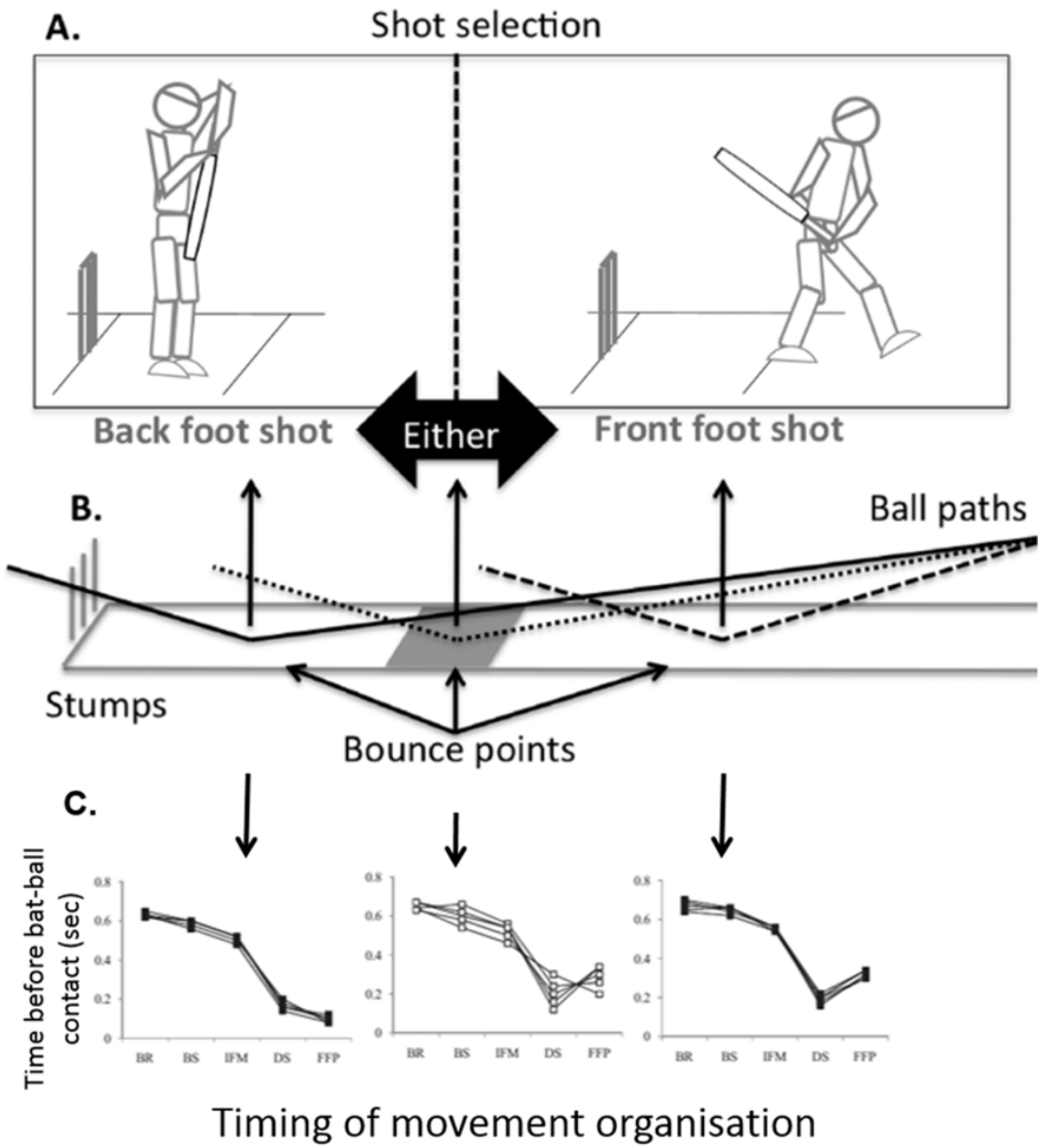

Figure 2-3. The relationship between constraints manipulation and movement variability in cricket batting. **BR** = ball release; **BS** = backswing initiation; **IFM** = initial foot movement; **DS** = downswing initiation; **FFP** = final foot placement.

The importance of environmental sources of variability in the skilled organization of movement was further emphasized in the meta-analysis by Mann et al., (2007) who commented that, 'the primary differentiation between expertise levels occurs when confronted with more complex operations that occur rapidly, lack regularity, and are unpredictable' (p. 473). Mann et al., (2007) revealed that the manner by which the testing stimulus was delivered to participants (static slide, video and field presentation tasks) induced differences in response accuracy and gaze behaviour (p. 474). Specifically, the largest effect, in terms of expert-novice differences, was reported in field studies, followed by video and finally the smallest effects were shown in studies using a static slide presentation paradigm. Mann et al., (2007) showed that representing perceptual variables, in terms of their three dimensional and dynamic characteristics, is the most effective approach for experimental tasks concerned with understanding expert-novice differences and, therefore, acquired adaptive behaviour more generally.

2.3.3 Experience related and contextual factors constrain performance

The goal-directed nature of physical activities, such as to win, achieve a certain time or distance, also means that performance can be constrained by contextual factors intimately connected to the performance context (Sampaio & Maçãs, 2012). Abernethy et al., (2001) suggested that experienced individuals may exploit sources of information that are static but none-the-less convey meaning due to their contextual relevance for the experienced individual. For example, although a useful tactic for an opponent might be to randomize behaviour, strategic concerns supersede this approach. For example, according to Abernethy et al., (2001) the center of the court in squash supports a better balance in defensive and offensive actions, making it more likely that an opponent will make shots with respect to (re)gaining situational advantage on the court. *Situational probabilities* can therefore influence how an experienced individual coordinates behaviour in advance based on their prior experience with a specific performance context (see also (Rosalie & Müller, 2013b)).

As the timescale of performance is extended, individuals exhibit behavioural tendencies revealed during the time course of a match that can be relevant when individuals or teams interact on a single or over separate occasions throughout a competition season (Lames & McGarry, 2007; McGarry et al., 2002; Sève, Saury, Ria, & Durand, 2003). Abernethy et al., (2001) argued that information from the dynamics of game play improved the ability of experienced squash players to perceive their opponent's intentions before they actually begin moving. *Intentions*, referring to the individuals underpinning behavioural goals (Juarrero, 1999). Sève et al., (2003) for example, interviewed experienced table tennis players using self-confrontation of videos of their matches. It was shown that that initially, players went through an 'enquiry phase', exploring the effectiveness of different performance actions through adopting a variety of different types of shots, in order to learn about the opponent's weaknesses, strengths and strategies. Following this period of *exploration* (behaviour that was primarily information gathering (Pijpers, Oudejans, Bakker, & Beek, 2006)), players settled to a phase of *performance*, where, 'players seek optimal playing effectiveness by reproducing the strokes they identify as perturbing to the opponent...' In paraphrasing Sève et al., (2003), exploration was found to be important to all performers across all competitive match-ups, even in cases where the individual knew the opponent, as they could not rely on predicting the events of a current match due to how features of an opponent's game differ within and across matches (p. 79) (for supporting data see also, McGarry and Franks (1994, 1996)).

A good example of how experience and contextual factors constrain coordination is also shown in the case of climbing. Experienced individuals, for example, when climbing on artificial indoor surfaces as opposed to outdoor, natural rock surfaces, tend to climb with greater certainty, exhibiting less exploratory behavior in the indoor context. Using Figure 2.4 to exemplify, it is shown that in an outdoor environment, experienced climbers tend to increase the amount of exploration. In the data presented, an experienced climber was asked to climb an indoor (upper graph) and an outdoor route (lower graph). The routes were matched for difficulty, length, number of holds and in how the holds could be grasped. In the outdoor route it was observed that the climber tended to explore hold properties both hands and feet. Specifically 49 performatory actions (where the climber used a hold to support the body weight; denoted as 'grasp' for the hands or 'support' for the feet) were recorded against 27 exploratory actions (where the climber would touch a hold but not use it to support the body weight and the next action was to reposition the limb to another or separate hold, exploration in Figure 2.4 is denoted as 'explore' for both the hands and feet). When climbing on the indoor route, however, this individual did not exhibit any exploration and completed the route in half the time.

One of the reasons for these results is that the outdoor environment contains considerably greater uncertainty in terms of what the holds afford the individual. For example, in the indoor setting because holds are artificial, of the same colour and bolted to a wall (itself with a different texture and colour to the holds), enhances the holds level of contrast. Consequently holds in the indoor context are not only easier to locate, but the climber can form expectations that holds will be strong enough to support their body weight. In the outdoor context, holds also vary in terms of fragility and induce to individual to ensure that their body weight can be supported (Davids, Brymer, Seifert, & Orth, 2014).

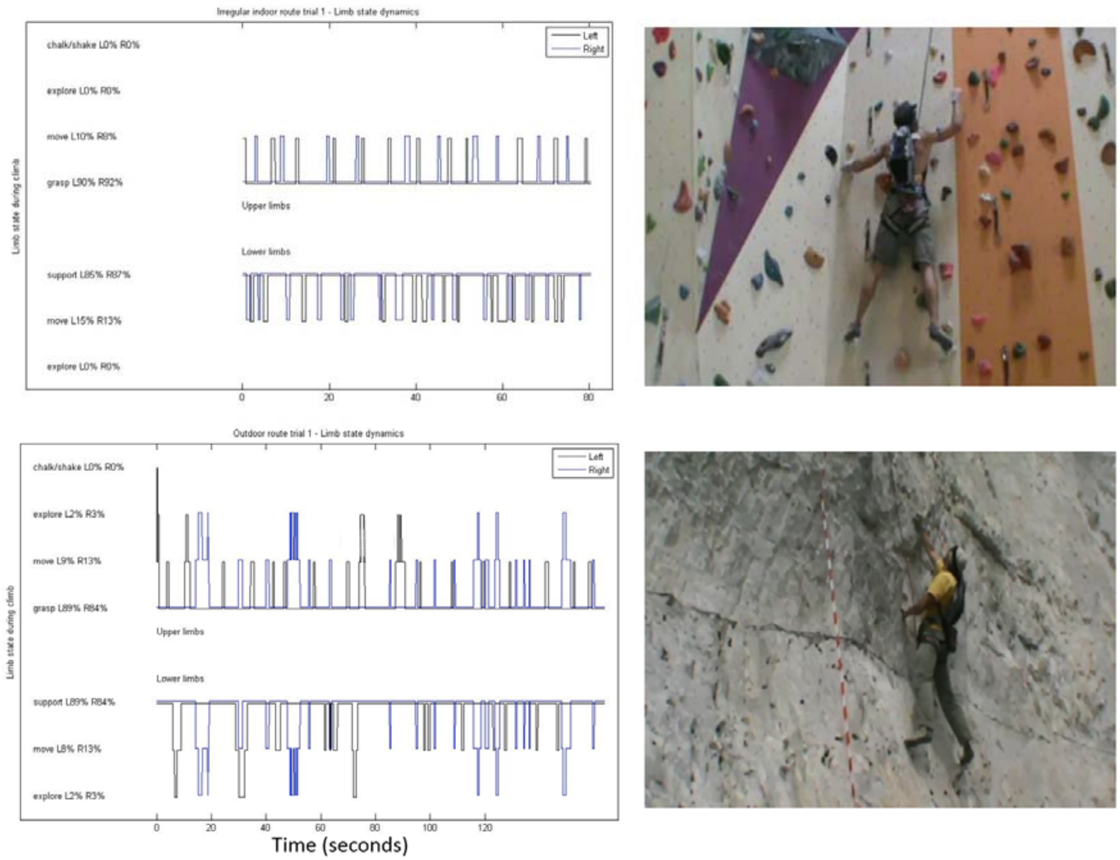

Figure 2-4. Individual comparison of the amount of time devoted to exploration and performance when climbing on an indoor route versus an outdoor route.

In summary, a primary concern in understanding functional movement variability, is that experimental design can fail to allow individuals to transfer skills that underpin their experience level to the experimental setting or to an intended environment following intervention. On the one hand, in order to maintain the adaptability of a movement pattern, according to Gibson (1966, 1979), an enriched perceptual environment, has several informational sources available that can be utilized to organize a stable coordination mode. Similarly, an enriched action environment, has several coordination modes that may be used as effective solutions to the performance constraints (Kugler & Turvey, 1987). Finally, specific dynamic and contextual features of performance also constrain behaviour (Abernethy et al., 2001). The key ideas underpinning experimental design for observing adaptive behaviour as presented throughout this section are summarized in below in Figure 2.5.

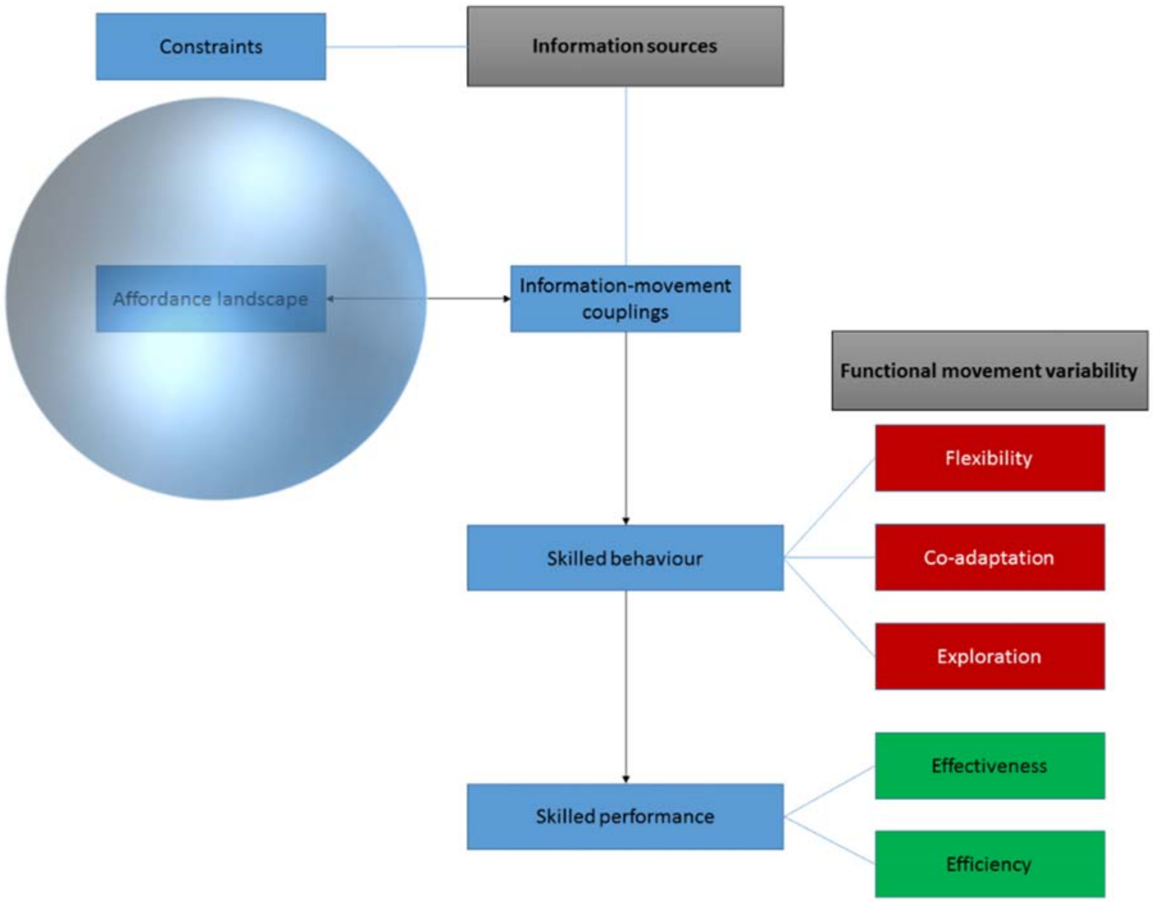

Figure 2-5. Key ideas underpinning performance in complex multi-articular tasks.

Figure 2.5 summarises that two key sources of information are important for understanding skilled behaviour. Firstly constraints (interacting task, environmental and individual factors) determine the affordances available within a performance contexts. Secondly, information-movement couplings that are formed by the individuals relationship with the constrained landscape of affordances and involving the acceptance or rejection of affordances. How the individual adapts to these information sources is revealed as changes in coordination patterns, co-adaptive movements, and exploratory behaviour (i.e., functional movement variability). Finally, skilled behaviour is also linked to the ability to achieve skilled outcome performance and is one of necessary the criteria determining the individual's ability to achieve the task.

2.3.4 Evaluating experimental design using properties of natural performance contexts: the representative design perspective

A major challenge therefore in understanding FMV is to 'design empirical task constraints that accurately sample the information and actions required for performance in specific performance contexts' (Travassos et al., 2013, p. 212). Brunswik (1956) used the term represent, when originally defining *representative design* as the arrangement of constraints in an experimental design in a manner sampled from the behavioural setting to which the results are intended to apply (see also, Hammond and Stewart (2001) and Hoffman et al. (1993)). Representative design is achieved when emergent behaviours and information-movement relationships used in one context can be observed in another context, and, thereby, support the external validity of constraints and behaviour (Araújo et al., 2007; Dhami, Hertwig, & Hoffrage, 2004). According to Dhami et al. (2004), determining the representative design of a performance or learning setting involves substantive situational sampling, where through preliminary work, key constraints and behavioural characteristics are uncovered. Specifically *substantive situational sampling* requires pilot work, interview and literature reviews in order that rational is developed for underpinning claims that findings can translate into hypothetical real-world cases (Dhami et al., 2004).

Representative design principles can, therefore, be used for evaluating whether experimental contexts support conditions for understanding the functional role of movement variability during performance. To this end, Pinder et al. (2011b) recently proposed *representative learning design* as a framework for determining whether a test or performance context can allow an individual to act in a functional manner. According to Pinder et al. (2011b), representative learning design can be construed from measures of action fidelity, outcome performance and information-movement couplings (these ideas summarised in Figure 2.6 below). *Action fidelity* referring to when performance under the training context transfers to behaviour that the training context simulates where, according to Stroffregen et al. (2003), an appropriate measure of action fidelity is the transfer of skill. Indeed, one of the key predictions of representative design is that the transfer of complex, multi-articular skill is evident between representative and intended contexts.

2.4 Representative learning design: Behaviour at the outset, during and after learning

Pinder et al., (2011b) recommended that 'to attain representative learning design, practitioners should design dynamic interventions that consider interacting constraints on movement behaviours, adequately sample informational variables from the specific performance environments, and ensure the functional coupling between perception and action processes' (p. 151). Although Pinder et al., (2011b) provide a detailed approach to the assessment of representative behaviour of skilled individuals, a significant limitation in the representative learning design framework is that there is no indication as to what representative learning behaviour resembles. Neither is there a clear indication, prior to, or after learning, what tests should be undertaken to determine if learning was representative. These are important limitations because there is no basis from which to develop specific hypotheses regarding what to expect prior to during or after an intervention with regards to skills development and transfer in a sport or physical activity setting.

For example, according to Newell (1986) skill acquisition is proposed as *a search* for functional coordination solutions that emerge from individual, task-oriented and environmental constraints (see also (Gel'fand & Tsetlin, 1962; Jacobs & Michaels, 2007; Teulier, Nourrit, & Delignières, 2006; Thelen, 1995; Van der Kamp & Savelsbergh, 1994)). This suggests that characterising a learner in a representative context can involve the emergence of functionally distinct forms of movement variability such as exploratory and/or transitional behaviour (Newell, 1996). Additionally, as outlined above, prior to learning, initial skills such as stable tendencies of coordination, represent an initial backdrop against which new forms of skilled behaviour are acquired (Kostrubiec et al., 2012; Teulier et al., 2006; Zanone & Kelso, 1992). Thus, in addition to determining if an individual can transfer skill to an intended context, some way of integrating an understanding of the initial and after learning state of the individual seems essential for determining the effectiveness of a representative learning design intervention.

The following section is therefore concerned with reviewing the existing research to have observed learning in complex multi-articular tasks (those involving the entire body and with an emphasis on forming a coordinative solution with respect to achieving a goal directed task). Studies that were identified this way included those that use a novel task to induce learning, and those that utilise an intervention to induced variability. The aim of this section was to integrate the empirical data from these studies into a framework for developing predictions related to learning behaviour in representative contexts

2.4.1 The role of coordination and control in complex multi-articular task

Following Newell's model of motor learning (Newell, 1986), learners can be considered as being in a coordinative, control or skill stage of learning. The *coordination stage* is characterised as the learner needing to establish basic relationships amongst the movement systems degrees of freedom and the environment. During the coordination stage, the learner might therefore exhibit variability in the types of movement strategies adopted, indicating exploration of qualitatively different ways of organising the movement system (Chow, Davids, Button, & Rein, 2008; Teulier & Delignières, 2007). In recalling Figure 2.1, an individual with no climbing experience might, when faced with a choice of how to grasp a climbing hold with multiple edges may be expected to explore a variety of different grasping actions or ways of using the hold. For example Seifert et al. (2013) showed that in beginner climbers, when required to climb a route designed with multiple grasping types, tended to use a greater variety of grasping actions which resolved over time with practice.

In the *control stage*, learners may have located a functional coordination pattern that they begin to refine through varying different movement parameters such as timing or position. For example, the continuous, linear improvement in performance when actions are practiced under fixed constraints may be a consequence of ongoing practice in the control stage (Newell et al., 2001). Again, taking an example in climbing, Cordier et al. (1993; 1994) showed that over ten trials of practice on the same climbing route, experienced individuals rapidly improved performance to an asymptote level after three trials. When plotting the performance data on a logarithmic curve, a linear function best fit the data. This would suggest that the experienced climbers did not explore different coordination solutions but rather, adapted very rapidly to the new task to emphasis a refinement of performance with practice.

In the final stage of Newell's model, the *skilled stage*, the individual optimally balances efficiency with effectiveness such as by exploiting passive or reactive forces generated between limb segments during movement (Davids et al., 2015). Optimized behaviour is characterized by smoothness and fluency (Newell, 1996). *Smoothness* for example can refer to the organization of actions around a minimization of jerk (the third derivative of displacement, (Hreljac & Martin, 1993)). *Fluency* refers to the capacity to link of movements in the spatial and temporal domains (Cordier et al., 1994). Skilled individuals maintain smooth and fluid action, under noisy, uncertain and dynamic contexts because the coordination of their movement system is more open to regulation by key constraints in the environment (Araújo, Davids, & Hristovski, 2006; Vereijken, van Emmerik, Whiting, & Newell, 1992). For example, recalling the study by Cordier et al., (1993; 1994), these studies involved two groups of experienced climbers at different skill levels. Their data showed that whilst both groups improved performance in a linear fashion, the less experienced climbers did not achieve, even after ten trials of practice, the same level of performance as the more experienced group. Hence, even with established techniques and extensive practice, individuals may still develop new coordinative solutions that can improve performance. A very straightforward example is given in how high-jump performance saw a sharp increase with the discovery of the Frosbury flop technique which emerged from the implementation of a new form of safety equipment and capacity of skilled athletes to reorganise behaviour accordingly (Farrow & Kemp, 2006). Thus throughout all levels of skill, the potential for new skills to emerge on the basis of changing constraints is possible and in most cases necessary necessary. For example, in sport and physical activity contexts, rules, equipment, technologies and social constraints continuously evolve to influence the performance land-scape (Davids et al., 2015).

2.4.2 Behaviour during learning a novel complex multi-articular skill

2.4.2.1 Exploratory behaviour supports the location of new movement patterns

One of the central features of new skill learning is the role of exploratory behaviour when faced with novel constraints (Newell, 1996; Thelen, 1995; Van der Kamp & Savelsbergh, 1994). Chen et al., (2005) for example observed individuals on a pedelo locomotion device over seven days of practice with 50 trials per day. The authors reported notably larger variabilities in movement pattern difference scores on the first day of practice compared to the final six days. This, according to the authors, suggesting that the learners converged toward a fixed coordination solution early in practice which was then further refined with practice (for similar results see (Caillou, Nourrit, Deschamps, Lauriot, & Delignieres, 2002; Hong & Newell, 2006; Ko, Challis, & Newell, 2003)).

2.4.2.2 Existing skills constrain the nature of learning behaviour

Individuals also display different responses during learning to a given set of constraints which may influence the nature and/or rate of learning (de Vries, Withagen, & Zaal, 2015; Liu, Mayer-Kress, & Newell, 2006; Teulier et al., 2006; Vegter, Lamoth, de Groot, Veeger, & van der Woude, 2014). For example, Nourrit et al., (2003) observed five beginners over 39 trials of practice revealing at the individual level of analysis examples of: linear improvement; transitional; and, complete lack of improvement. Caillou et al. (2002) also showed how intrinsic dynamics can influence learning. They observed practice in a ski simulator task and showed that a bias based on limb dominance was evident in the performance dynamics. Specifically, whilst the right leg was used to generate force, the left leg was used as support (Caillou et al., 2002) (see also, (Hong & Newell, 2006)). This suggesting that the individuals limb dominance begins to shape behaviour in early learning. Indeed, according to Nourrit et al., (2003) different routes to learning may occur that depend on the intrinsic dynamics of the learner and the level of competition of the to-be-learned pattern with already established attractors (for work in simple movement models refer to (Kostrubiec, Tallet, & Zanone, 2006; Kostrubiec et al., 2012; Zanone & Kelso, 1992)).

2.4.2.3 Novel skill learning can exhibit non-linearity's based on the relationship between existing skills and the difficulty of the new skill

In some cases during learning, individuals have been observed returning to 'old' movement patterns during the process of transitioning to a new skill (Chow et al., 2008; Teulier et al., 2006). For example, Teulier and Delignières undertook an experiment involving 100 trials of practice on ski simulator device, describing a period where some beginners would alternate between an early movement pattern and the new emergent behaviour. According the Teulier and Delignières this prolonged phase transition was because the beginners were using the early pattern as a fall back option to then recommence exploration of the to-be-learned movement pattern (also noted in (Delignières, Marmelat, & Torre, 2011; Teulier et al., 2006)) and suggests that individuals can develop a variety of strategies during learning to explore new movement patterns.

Of additional concern when observing learning is that the individual may need substantial time to practice in order to locate the new movement solution. For example, Delignières et al., (1998) found that beginners and experienced gymnasts differed significantly in up-side-down swinging on parallel bars, both in terms of relative phase and frequency ratio between upward and vertical oscillations of the centre of mass (COM). Whilst beginners spontaneously adopted a coordination mode characterized with a 1:1 frequency ratio and in-phase pattern, the experienced gymnasts used a 2:1 frequency ratio and 90/270° phase offset allowing them to achieve significantly larger swing amplitudes compared to the beginners. The beginners were then given 80 practice trials over eight sessions with the goal of improving swing amplitude. It was found that no change in the coordination solution emerged in the group of beginners, although improvements in movement amplitude were recorded (for a similar outcome despite extensive practice see (Komar, Chow, Chollet, & Seifert, 2014)). According to the authors, the reason for a lack a of transition may have been due to the difficulty in overcoming the initial coordination mode. For example, in a related study, Teullier and Delignières (2007), observed that whilst a similar phase and frequency relationship differentiated the movement patterns of beginners and experienced individuals in a ski simulator task, because, the ski task was more comfortable for participants, allowing them to practice in a standing position, they were able to more readily locate the new, more advanced coordination mode, successfully undergoing transition.

2.4.2.4 The need to supporting learning through experimental design

These data, raise the concern that the complexity of the learning context influences availability of coordinative solutions and the time required in which to learn them. For example, in representative learning contexts, it can be expected that multiple systems (such as muscular and neural systems) evolve at different rates, meaning extended practice can be needed to effectively explore a given state space (Thelen, 1995). For example Vereijken et al., (1997) observed that, even in the very stable multi-articular task context of learning on a ski simulator, three qualitatively distinct movement patterns were observed when practiced over 7 days. The first, characterised as an inverted pendulum, resolved rapidly after a single day of practice to be characterised as a hanging pendulum with the third coordination solution (characterised as a compound buckling pendulum) emerging after around six days of practice (Vereijken et al., 1997) (see also, (Delignières, Nourrit, Deschamps, Lauriot, & Caillou, 1999; Nourrit et al., 2003; Nourrit, Deschamps, Lauriot, Caillou, & Delignieres, 2000)). Indeed, early coordination patterns, although apparently ineffectual for generating amplitude, may have been functional for addressing early constraints on the learner such as stability. For example, Chow et al. (2005) cited in (Renshaw, Chow, Davids, & Hammond, 2010), observed learners kicking over a height constraint to targets visible on the other side for 12 sessions of practice over 4 weeks. Early in the kicking task, the participants primarily focussed on kicking for height. As participants were able to clear the height barrier more consistently and successfully, they concentrated on ensuring that the ball landed accurately on the target. Specifically, as the height constraint decayed in importance, the accuracy constraint emerged as increasingly important to the learners and their subsequent search for an appropriate coordination solution. In this case, the decay or emergence of task constraints demonstrates that the function of learning behaviours can change over time with respect to the evolving perceptual-motor landscape.

Another reason new more functional behaviours may not emerge after substantial practice, as shown the study by Delignières et al. (1998), is that in natural practice settings, information is typically made available to support changes in the coordination pattern (Moy et al., 2014). Such information may be in the form of feedback (Sigrist, Rauter, Riener, & Wolf, 2013), instruction (Barris et al., 2014; Boschker & Bakker, 2002; Chow, Koh, Davids, Button, & Rein, 2014; Komar et al., 2014; Lee, Chow, Komar, Tan, & Button, 2014) or environmental augmentation (Seifert, Orth, et al., 2014; Seifert, Orth, et al., 2013). And furthermore, natural learning contexts tend to contain substantially greater levels of variability across all manner of constraints, such as from coaches, peers, or different technologies, all of which may facilitate exploration (Greenwood, Davids, & Renshaw, 2014; E. Phillips, Farrow, Ball, & Helmer, 2013). Newell (1991) referred to information that supports the emergence of new coordination modes as *transitional information*. When used in applied contexts transitional information is intended to facilitate the emergence of new or more adaptive behaviour (Chow, 2013). Whilst in some cases, relying on the intentions of the individual to generate transitional information may be an effective strategy, in other cases it has proven insufficient (Boschker & Bakker, 2002; Chow et al., 2008; Delignières et al., 1998; Komar et al., 2014).

Chow et al., (2008), for example, showed that at the individual level of analysis, whilst some individuals can show extensive exploration of different movement patterns during practice, others can show little variation from one session to the next. Specifically, Chow et al. (2008) observed four individuals with no experience playing ball games involving kicking. Observed were their spontaneous practice behaviour in a ball kicking task over 4 weeks involving 3 sessions per week, and 20 trials per session. It was shown that whilst each individual improved performance in linear fashion, cluster analysis on the inter-limb angular relationships for each kick revealed that most individuals explored between 6-12 different kicking techniques over the 4 weeks, however, one individual only explored 3 kicking techniques. What was striking for this individual was that out of 240 trials, 1 pattern was used once, another was used twice, with the third used the remaining 237 trials. Similarly, Boschker and Bakker (2002) also demonstrated that a group of beginners in a climbing task who were shown (and instructed) on how to use an advanced coordination pattern, immediately displayed better climbing performance compared to groups that were not shown the pattern. Of additional concern is that, despite practice, the control group in this study, who were instructed to climb as they liked, never began to use the advanced coordination pattern. Finally, a study involving two groups of beginners in a breast-stroke swimming task revealed that under conditions that did not guide the learners, individuals did not locate more advanced coordination solutions. Komar et al., (2014) observed two groups of beginner swimmers in a pre- post-test design manipulating the instructions under which each swimming session was practiced. The practice volume involved two sessions of practice per week over 8 weeks and involving 10 swum laps using the breast-stroke technique. One group was instructed to swim obeying the rules of breast-stroke technique. The second group, in addition, were instructed to glide 2 seconds with the arms outstretched. The results showed that whilst the intervention group shifted their coordination pattern toward one exhibited by advanced swimmers, the group who were not given any specific instructions did not show a transition toward to the more advanced coordination pattern.

The studies by Chow et al. (2008), Boschker and Bakker (2002) and Komar et al. (2014) demonstrate that if the intention of the practitioner is to induce an exploration of the perceptual-motor landscape during learning, relying on the spontaneous intentions of the individual may not be a sufficient condition for them to undergo a transition toward a new mode of coordination. Additionally, the findings presented in Chow et al. (2008) show no clear link between exploration as a necessary behaviour for improving skilled performance. In this regard, a key limitation shared across the studies discussed above, is that they do not test the transfer of skill and, because of this, the relationship between exploratory behaviour and the transfer of skill is impossible to determine. Whilst the evidence in literature to report learning behaviour in multi-articular tasks have effectively linked transitional phenomena to exploratory behaviour as a key mechanism underpinning the emergence of new skills, a salient criticism is that these tasks rarely resemble physical activity contexts, nor are the skills acquired considered with respect to their generalisability to the real world contexts from which the task was initially drawn from. To the exception of climbing and swimming tasks, the tasks identified above may be better be described as inter alia movement models, providing significant insight into skill acquisition of individuals faced with a novel multi-articular action (Davids, Button, Araújo, Renshaw, & Hristovski, 2006). Furthermore, most of the previous motor learning studies have been designed to test movement coordination in discrete interceptive tasks (kicking) or in cyclical continuous tasks (swimming or ski belt oscillations). Given that participation in many physical activities pertains to tasks that nest cyclical locomotor behaviour with a rich mixture of discrete actions, a research vehicle where individuals' use both locomotion and discrete actions, such as climbing, might be fruitful to further develop.

Providing clear guidelines regarding learning in representative tasks is dependent to what extent the learning behaviours discussed above might reflect learning behaviour in the sorts of tasks that individuals normally intend to participate and/or to what extent the skills acquired in these tasks transfer to an intended context. For example, whilst there is a tacit belief that instructions or environmental manipulations that support exploration can result in more effective learning outcomes in comparison to more repetitive, prescriptive designs (Buszard, Farrow, Reid, & Masters, 2014; Guadagnoli & Lee, 2004; Rendell, Masters, Farrow, & Morris, 2010; Schöllhorn et al., 2009; Wulf, McConnel, Gärtner, & Schwarz, 2002) this is not always the case (Lee et al., 2014).

2.4.3 Intervention studies: does more extensive exploration during learning improve skill acquisition in complex multi-articular tasks?

When variability during practice is induced the ability to transfer skill to a modified set of constraints can be improved. The mechanisms that underpin improved performance have been linked to a more extensive exploration of the perceptual-motor workspace, where induced movement variability provides information that drive adaptations during learning that may then support performance under conditions of transfer (Chow et al., 2011; Lin, Fisher, Winstein, Wu, & Gordon, 2008; Schöllhorn et al., 2009). The following section is focused on how constraints manipulation have been used to induce learning and improve transfer, seeking to determine whether these effects can be explained on the basis of induced movement variability.

Even in experienced individuals, constraints manipulation can induce learning effects (Cordier et al., 1994; Seifert, Orth, et al., 2014) and may lead to the individual's ability to use movement variability to improve performance (Barris et al., 2014). According to Guadagnoli and Lee (2004) for learning to occur, information is required that differs as a function of the individuals skill and the task difficulty of the to-be-learned task. *Functional task difficulty* refers to how challenging the task is relative to the skill level of the individual performing the task and the conditions under which it is being performed (Guadagnoli & Lee, 2004). Modifying the degree of uncertainty in tasks through constraints manipulation is therefore a mechanism for inducing learning because it establishes the conditions that require a search for a functional solution and/or the adaption of movement to maintain stability.

Supporting this are, recent, studies showing that progressively increasing the amount of variation in practice scheduling during learning interventions involving complex multi-articular skills, can improve retention and transfer of skill (Porter & Magill, 2010; Porter & Saemi, 2010). For example, Porter and Magill (2010) undertook two experiments. In the first experiment, low experienced individuals were placed into three different conditions and required to practice 81 trials per session over 9 sessions. The task involved golf putting to a target from three separate distances (27 trials per distance). The *blocked only condition* required 27 consecutive trials of each condition per session (e.g., AAA–BBB–CCC). The *random practice condition* randomised the condition practiced throughout each session (e.g., ACB–BCA–CAB). Finally an *increasing condition* required that for the first 27 trials, a blocked order of practice was given, then, for trials 28 to 54 a serial schedule was used (where conditions were repeatedly practiced in serial order (e.g., ABC–ABC–ABC)). The final 27 trials a random practice schedule was enforced. Under transfer conditions that involved different putting locations the increasing condition showed superior performance to both blocked and random practice conditions. In their second experiment, Porter and Magill (2010) applied the same scheduling as the first experiment but instead, individuals practiced three different ball throwing techniques (overhead, chest and single arm) from a fixed location. Similar to experiment 1, performance under transfer (a different location) after practicing in the increasing condition was superior to both blocked and random practice conditions. According the authors, one of the reasons learners could benefit from the increasing variability condition was it allowed the beginners to first stabilise the movement pattern, which then allowed them to benefit from the uncertainty induced by the variable practice order. Unfortunately the authors did not report the movement kinematics of the learners, and hence direct links to functional movement variability cannot be considered.

Taking a different approach to inducing variability during practice, Lee et al. (2014) undertook an intervention study comparing a *non-linear pedagogical approach* to a *prescriptive approach* controlling for practice volume. Individuals underwent 4 weeks of practice involving two sessions a week consisting of 80 trials of tennis ball hitting. The non-linear group experienced a broad range of constraints during practice including the manipulation of net height, target area, court size, and rules to achieve specific task goals. In the linear group, instructions involved having individuals learn a predefined movement pattern through the use of prescriptive cues and repetitive drills, which according to Lee et al. (2014) left negligible opportunity for exploration. In follow-up retention tests, it was found that the linear group showed better performance. However, the analysis of each individual's kinematics was also undertaken and revealed a greater number of movement patterns were present in the post test sessions in the non-linear group. These findings suggested that the greater exploration supported during practice helped develop degeneracy in the participants. Unfortunately in this study, no transfer test was undertaken to evaluate whether the enhanced exploration led to more effective transfer of skill.

Barris et al., (2014) undertook a practice intervention in natural conditions involving highly experienced individuals. In this study, a single group of internationally competitive springboard divers undertook a 12 week intervention, where during their normal practice sessions (10 per week), divers were requested to reduce the amount of aborted diving attempts (i.e. termed baulking). 5 trials during pre- post-test observations of the diver's inter-limb kinematics at key points throughout the dive preparation were recorded. It was shown that whilst topologically the same, the movement kinematics were significantly more variable from one trial to the next. These changes in movement variability were also reported alongside a significant reduction in baulked dives during the intervention, and improved consistency of the quality of the dive in the post-test. According to Barris et al., (2014) the changes implied adaptive behaviour in relationship to variation detected during the preparation for take-off. In this respect, the elite divers may have benefited during training from the requirement to continuously adapt to the subtle accumulation of variability typically seen during the preparation to perform nested tasks (in this case the dive) (Montagne et al., 2000). Unfortunately however, in this study, no control group was included nor were the dynamics of learning observed throughout practice, thus, the degree to which changes in the movement pattern variability could be ascribed to the experimental intervention or the impact of being part of an elite level development squad is unclear.

2.4.4 Recommendations for evaluating representative learning design

In conclusion, this section has attempted to integrate the representative learning design framework with existing learning models and intervention studies involving complex multi-articular tasks. The ideas raised and their relationship to representative learning design have been summarised below in Figure 2.6 (an adaption from Pinder et al. (2011b)). According to the extant literature, a number expectations during skill acquisition under representative learning design conditions can be summarised. Specifically, representative learning behaviour may include: a) emergence of novel coordination patterns; b) resistance during learning based on to what extent the new movement pattern competes (or is dissimilar) to a to-be-learned solution; c) potential reuse of 'old' movement patterns during the search for other potentially more effective behaviour, and; d) emergence of individually specific behaviour, both in terms of the extent of exploration and in terms of the outcomes settled-upon.

The studies to have observed learning behaviour, also provide an empirical basis that behavioural meta-stability is linked with the emergence of new behaviours in multi-articular tasks (Teulier & Delignières, 2007). Additionally, the notion that practitioners can design constraints that facilitate the reinvestment of exiting skills during learning for exploring new potentially more effective behaviours is supported. For representative learning design interventions, practice settings that support variability, in particular in the form of different movement patterns, are predicted to result in more substantial inter-individual and intra-individual differences in movement patterning. Currently the extent to which these phenomena can support the transfer of skill is unconfirmed. Future research is needed to understand: a) how learning in representative contexts influences the nature of the initial intrinsic dynamics of the individual (for example does it lead to greater multi-stability), and; b) whether the acquired skill can be shown to transfer to an intended context.

Finally, as highlighted previously, providing clear guidelines regarding learning in representative tasks is dependent to what extent the learning behaviours involving inter alia movement models such as the ski simulator or ball kicking reflect learning behaviour in the sorts of tasks that individuals normally intend to participate. Hence, future research should be directed towards observing learning dynamics in physical activity or sport performance settings (such as exemplified in (Barris et al., 2014; Boschker & Bakker, 2002; Farrow & Reid, 2010; Komar et al., 2014; Lee et al., 2014)).

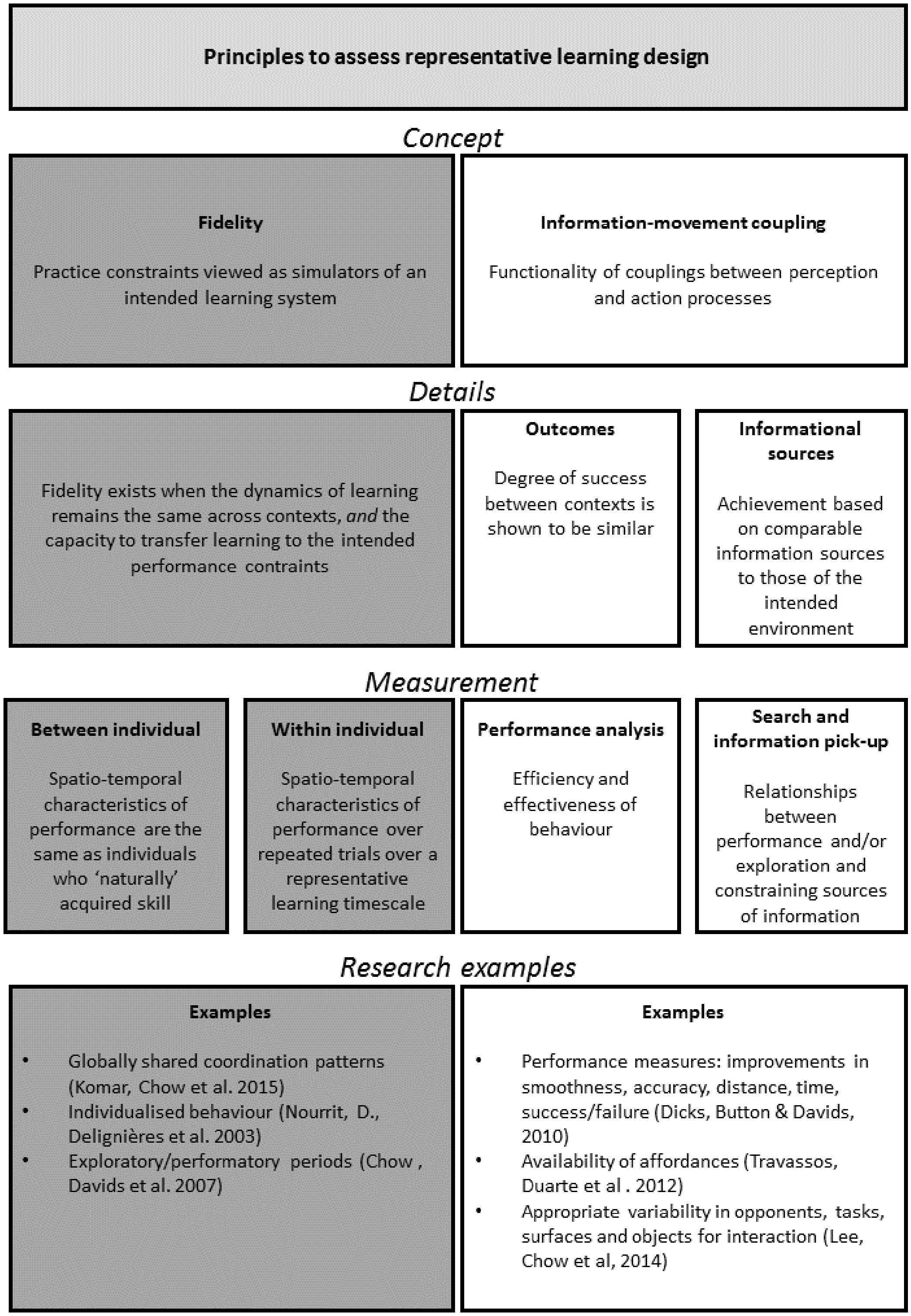

Figure 2-6. Representative learning design framework integrated with respect to learning phenomena.

2.5 Future research priorities: Understanding mechanisms in the acquisition of complex multi-articular skill in representative learning design settings

2.5.1 Determining the impact of intervention on intrinsic dynamics and the transfer of skill

After reviewing what representative learning behaviour may resemble, a criticism of the above learning and intervention studies, are that few might claim to have reported learning behaviour in a representative learning context. In addition to this concern, is that studies to have undertaken interventions have primarily relied on using retention tests to characterise the outcome of learning as opposed to transfer tests or some measure of the individual's coordination. In r*etention tests* performance is measured under the same conditions of practice, usually after a delay. For this reason, there remains little evidence that, after practice, participants perform in a manner corresponding to individuals who have 'naturally' acquired their skill. Because in natural performance contexts, constraints are inherently uncertain (e.g., different opponents, initial environmental conditions, changes in conditions over time etc.) alternative tests are recommended.

That is, following learning interventions in complex multi-articular skills, the use of transfer tests and scanning procedures might be more appropriate. *Transfer tests* refer to performance tests that are different to the constraints of practice and which can occur along different dimensions. The purpose of a *scanning procedure* is to assess an individual's multi-stability. For example, prior to learning a new skill, a scanning procedure can uncover the pre-existing stable and unstable coordination tendencies when performing in a given context and then determine how the landscape is affected by practice under a specific arrangement of constraints (Kostrubiec et al., 2012; Zanone & Kelso, 1992). The approach involves scaling a parameter such as a required position and observing effects on overall movement coordination and stability. For examples see: locomotion activities (Jordan et al., 2007; Seifert, Chollet, & Rouard, 2007), basketball shooting (Rein, Davids, & Button, 2010), reaching and grasping (Kelso, Buchanan, & Murata, 1994; Mutsaarts, Steenbergen, & Meulenbroek, 2004) and interceptive actions (Hristovski, Davids, & Araújo, 2006; Pinder et al., 2012; Sørensen, Ingvaldsen, & Whiting, 2001). The key findings from these studies are that more experienced individual tend to maintain performance as constraints are scaled that challenge the individuals coordination, exposing the underlying parameters used to adapt to the changing conditions.

As already highlighted, scanning procedures may be important for understanding an individual's response to intervention. For example, in reiterating Kostrubiec et al. (2012), learning can involve a simple shift of a stable coordinative state in the direction of the to-be-learned pattern characterised as an evolution of the initial coordination dynamics based on scaling spatial and temporal parameters, similar to the description of control stage of learning. Whereas on the other hand, individuals can exhibit non-linear abrupt transition in the nature of the coordination solution during practice, suggestive of the emergence of a new pattern or skill through transition, this suggesting the passing from a coordination to a control stage of learning. According to Kostrubiec et al. (2012) the route of learning is dependent on the initial intrinsic dynamics of the individual and how much the environmental demands compete or cooperate with the individuals existing intrinsic dynamics. Hence, in addition to using a transfer test, some measure of the individual's intrinsic dynamics prior to and after learning seems appropriate for understanding the full implications of a learning intervention.

2.5.2 Specific and general dimensions that support the transfer of skill and learning

Echoing an ongoing theme in this chapter, Rosalie and Müller (2012) commented that most studies have failed to consider the underlying mechanisms, contextual factors, and extent of adaptation that may contribute to transfer. Issurin (2013) recently provided a model for how transfer phenomena can be observed in terms of the amount of change in a given performance index taken in reference to the practice and transfer context (see Figure 2.7 below) (see also (O'keeffe, Harrison, & Smyth, 2007)). According to both Issurin (2013) and Rosalie and Müller (2012), transfer can be understood along specific and general dimensions.

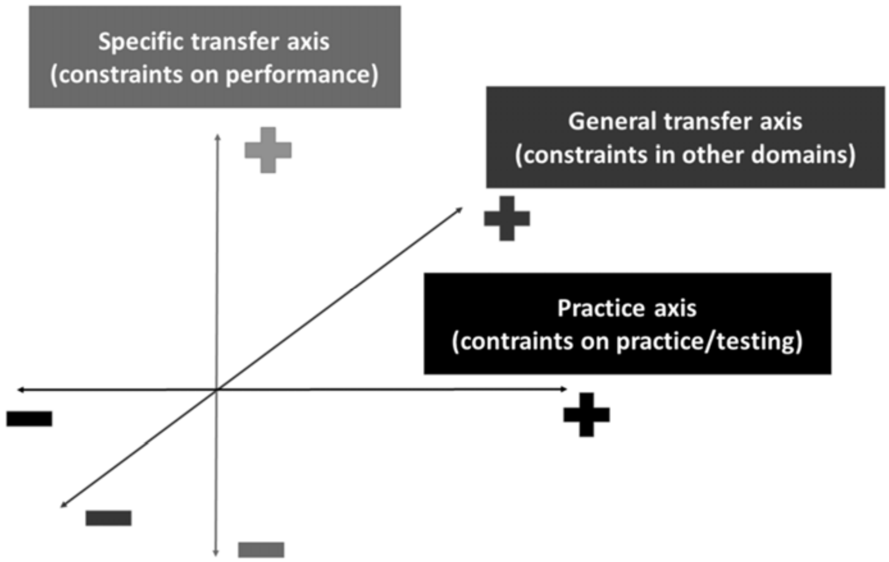

Figure 2-7. Conceptual approach to measuring general and specific transfer.

Referring to Figure 2.7, which was adapted in part from Issurin (2013), one approach to understanding transfer can be through considering change in a selected perceptual-motor variable to indicate the impact of an intervention on transfer of skill along different dimensions. For example, if after practice, improvement can be shown along either axis, a positive transfer effect, is attributed to the intervention. Determining the nature of transfer, specific or general, depends on how constraints are designed in the transfer and practice tasks. For example, FMV might support the general transfer of skill in so far that learning under ecological constraints (e.g. gravity, wind-resistance, uncertainty) can support effective behaviour in a separate domain. On the other hand, a specific form of transfer might be supported by adaptations to types of information only found a given practice ecology.

One way to conceptualise specific and general transfer mechanisms has been to consider performance in activities of shared and different task categories. Individuals who practice extensively in an activity within a given category may have greater performance (transfer of skill), or more rapid learning (transfer of learning) in another sport classified within the same category (such as tennis and cricket (Rosalie & Müller, 2012)). One reason for this may be that, when transferring skill within task categories, shared, specific, informational properties underpin performance, a mechanism referred to as *near transfer* (Rosalie & Müller, 2012). In interceptive sports, the transfer of skill from tennis to cricket, can be positive because experienced individuals have learnt to pick-up and co-adapt to advanced- and ball-flight information to perceive the nature, location and time the ball will arrive (Müller & Abernethy, 2012).

According to Jacobs and Michaels (2007), s*pecifying information* from local constraints provides the experienced individual with greater certainty regarding the usability of a constraining source of information. *Local constraints* referring to information sources that hold throughout a specific task situation. According to Gibson, specifying information provides the individual *knowledge of* the specific environment, describing that an individual can perceive the surrounding layout of the performance environment in the scale of body and action capabilities. For these reasons, in more experienced individuals, constraints on practice may need to be increasingly specific to achieve transfer of skill to the intended competitive context (Issurin, 2013). Issurin (2013) referred to this form of transfer as *vertical transfer*, occurring 'when acquired skills and abilities are exploited for the acquisition of more difficult and complex skills, which allow trainees to achieve a higher level of competence'. Hence transfer tests might be able to test specific transfer after an intervention by increasing functional task difficulty by manipulating control parameters that require to individual to act on specifying information.

Conversely, broadly referred to as *far transfer*, performance can also be facilitated through principle-based mechanisms, allowing the transfer of skill to activities across different domain categories (Rosalie & Müller, 2012). For example, Rosalie (2012) suggested that an ability to abstract behaviours such as visual exploration strategies might transfer between sports or activities (such as between a field, team based sport and an interceptive sport, (Rosalie & Müller, 2013a)). In a similar vein, Issurin (2013) suggested that *horizontal transfer* is 'when the outcomes of a training process can be utilized in a wide spectrum of tasks and situations of similar complexity and difficulty as the previous settings'. The role of movement variability in underpinning a general form of transfer might be that it can act as a mechanism for exploring new contexts, thus allowing an individual to more rapidly locate sources of information that support goal achievement. For example, Jacobs and Michaels (2007) referred to *ecological constraints* as sources of information that hold in the ecologies of particular animals. For humans, gravity, wind resistance, and uncertainty would be examples of ecological constraints that can form a basis from which to support general transfer of skill and learning. That it, experience of ecological constraints can provide a foundation from which to search out specifying sources of constraint unique to a new task context. Hence transfer tests to assess general transfer after an intervention might do so by taking an individual into a different performance environment.

Seifert et al., (2013) provides a good example of how coordination variability can support transfer of skill into different environments. Seifert et al., (2013) tested transfer of experienced rock climbers and inexperienced rock climbers in an unfamiliar ice-climbing environment. Climbing fluency, defined in terms of continuous vertical displacement, was related to an ability to use a greater repertoire of inter-limb coordination patterns that were unavailable to the inexperienced group (see Figure 2-8 below for details).

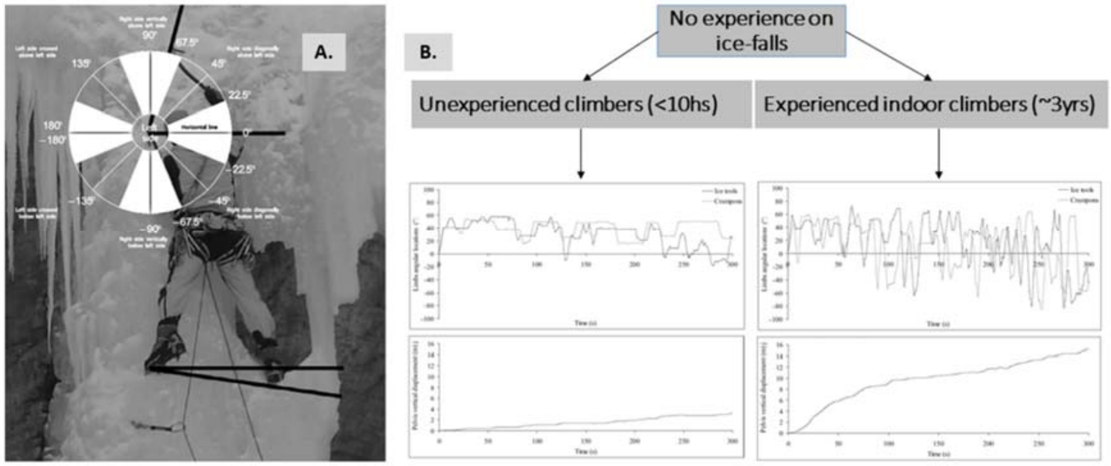

Figure 2-8. The relationship between movement variability and the transfer to of skill in ice climbing.

According to Seifert et al. (2013), the inter-limb movement variability supported a minimisation of prolonged pauses and an ability to use existing features of the ice-wall to achieve anchorage (shown in a lower ratio of ice-tool swinging to definitive anchorages). The successful transfer of the rock-climbers to the ice-climbing environment may have been due to their skills related to the gravitational constraints of climbing on vertically orientated surfaces. This would suggest that ecological constraints shared across different climbing contexts, supported the capacity to more readily locate specifying information in the local constraints in the ice-climbing context, such as how ice of different density may or may not support weight bearing anchorage.

2.5.3 The role of noise and meta-stability in complex multi-articular skill acquisition

During practice interventions that involve constraint induced variability, results are generally in favour of inducing variability for improved learning outcomes. For example, the use of a modified protocol of increasing the amount of variability within a practice session appears to support the transfer of skill in multi-articular tasks (Porter & Magill, 2010; Porter & Saemi, 2010). It is not entirely clear however, what the mechanism is that improves transfer. One of the potential candidates discussed by Porter and Magill (2010) for example, was that structure of practice was similar to the stages described in Newell's model of motor learning (1986), where individuals were given the opportunity to first stabilise their behaviour and overcome the coordination stage, which allowed them to benefit from the variability induced later in the practice session. However, because intervention studies have not included data of behaviour during learning it impossible to determine the impact of the constraints on the learning behaviour. Additionally, because transfer tests, or scanning procedures are so rarely reported, exactly how variability in practice scheduling has influenced learning remains unclear.

One explanation, adopting the dynamical systems framework provided by Huet et al., (2011), is that variability during practice acts like noise, preventing the individuals from becoming trapped in false minima in terms of the information relied on support performance. Specifically, Huet et al., (2011) found that variable practice conditions in a flight simulator were superior to constant practice conditions during a transfer test. During acquisition, that involved 180 trials of practice spread over 4 separate days, the variable practice group were exposed to variation from one trial to the next of three information variables that can be used to support landing performance (texture density of the ground surface, runway width and eye height) whereas in the constant practice conditions informational variables were fixed. According to Huet et al., (2011) the constant variability during practice acted like noise preventing stabilisation within a false minima, where the noisy learning conditions supported a more effective education of attention toward more useful informational variables unaffected by the constant variability.

Noise might, therefore, provide one way to explain why representative learning design contexts can improve skilled performance and transfer. The study by Barris et al. (2014) for example, might be interpreted in the respects, that, noise induced movement variability were beneficial for the elite performers. Although further research is needed involving control groups to confirm this, it would seem that the instruction to stop baulking resulted in an increase in functional movement variability.

During diving competitions, baulked dives are heavily penalised, hence it may be the instructions to follow through with dives were exposing the divers to more noise during the approach phase of the dive similar to the levels observed in competition.

In the study Lee et al. (2014), whilst performance under retention testing was not improved after practice in conditions that promoted extensive exploration, within individual movement pattern variability did increase. This result suggesting that learners under conditions that facilitated exploration supported the acquisition of a greater variety of hitting techniques. It is logical that the group that were prescribed a specific action outperformed the non-linear group under constraints similar to practice, possibly because they had practiced and refined the technique more. It would be interesting to determine whether or not individuals who acquire greater movement pattern variability can more effectively transfer their skills.

Finally, another potential mechanism that might facilitate the transfer of skill, and that has been extensively discussed is meta-stability. Meta-stability has been described across a range of tasks as corresponding to a transitional region of performance. In cricket, between different shot selections, in tennis, basketball and squash as between anti-phase and in-phase interpersonal coordination, in boxing tasks, between different striking actions and in climbing, choosing between grasping actions. Whilst, previous studies have investigated the role of constraints that induce meta-stability in experienced individuals (Hristovski, Davids, Araújo, et al., 2006; Pinder et al., 2012) trial effects have not been reported. Furthermore, whilst, many links have been argued between this system state and the emergence of new skills (Chow et al., 2011; Kelso, 2012), observation of learning under conditions that represent a metastable regime have not been reported. Hence, whilst the extant literature suggest that constraints that induce meta-stability during practice might be considered representative of the constraints on performance, the impact of learning under constraints that induce or represent meta-stability is clear a research priority.

2.6 Conclusion

This review has examined the position that the positive transfer of skill and learning, can be underpinned by perceptual-motor mechanisms related to functional movement variability. These ideas have been developed with the outlook, that the design of learning contexts should be informed by data that can characterise what performance and learning behaviour resembles in complex multi-articular tasks individuals normally seek to participate, such as sport or physical activity settings; and, that can provide clear evidence that after practicing under experimental conditions, participants can perform in a manner corresponding to individuals who have naturally acquired their skill. The specific aims addressed in this chapter have been to: a) evaluate factors that induce adaptive variability in complex multi-articular tasks, and; b) to consider FMV as a mechanism underpinning the transfer of skilled behaviour.

The role of FMV for performance identifiable across task categories has been linked to three key concepts: a) co-adaptation; b) change in coordination patterns and c) exploratory behaviour. The presence of FMV has been identified across numerous sport performance and physical actively settings. These studies highlight the importance of degeneracy in skilled individuals as potentially underpinning the ability adapt to changes in the environment and potentially reorganize the movement system if need be. Despite this, there is little evidence that movement variability supports transfer of skill or learning and future research should this question. Results, however, show that variability induced during practice can be achieved through specific arrangements of constraints that represent uncertainty, expose the individual to noise and encourage exploratory behaviour. According to representative design, the most straightforward mechanism for improved transfer after intervention is that arrangements of constraints on practice simulate similar arrangements of constraints under transfer conditions.

In order to provide clear design strategies for inducing movement variability during learning future research needs to consider: a) the characteristics of learning behaviour that leads to transfer and; b) determining whether learning has resulted in a capacity to perform in a manner corresponding to ‘natural’ experts. Providing clear guidelines on constraints manipulation during learning are reliant on developing research strategies that address these gaps. Therefore it is proposed that high priority should be placed on research that can sample performance, learning and its transfer under constraints representative of the complex environments that individuals normally participate, such as a physical or sport, with an active community of experts.

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CHAPTER 3. REVIEW PAPER 2: MOVEMENT MODEL

Coordination in climbing: effect of skill, practice and constraints manipulation

Table 3-1. Chapter 3 Table of contents.

Table 3-2. Chapter 3 Key points.

• Skilled climbing performance is characterised by smoothness (organisation of actions around a minimisation of jerk) and fluency (optimal linking of sub-movements in the spatial and temporal dimensions) in movement dynamics and hand-hold reaction forces. • Perceptual and movement adaptations, including gaze behaviour, limb activity and postural adjustment, appear to be optimised in elite climbers to support smoothness and fluency, and research priority should be placed on observing perception and movement during climbing tasks and determining their relationship to skilled climbing performance. • Scientists and coaches should interpret exploratory behaviour as a potential indicator of learning, and future research should determine if interventions that improve skill in climbing can be designed by manipulating task and environmental properties on the basis that they induce exploratory activity.

Abstract

Background: Climbing is a physical activity encompassing many sub-disciplines and there are currently no comprehensive reviews pertaining to coordination and it's acquisition.
Objective: The aim of this paper was to develop research priorities for skill learning in climbing. Measures of skilled climbing, including gaze position, limb and whole body dynamics, and hand-hold reaction forces were integrated and the impact of constraints on coordination of action during elite level performance; effects of skill; practice, and; environmental and task manipulation are summarised.
Methods: A systematic review of the measurement of perceptual and movement data during climbing tasks was conducted; permutations of terms related to 'climbing', 'skill', 'perception', 'movement' and 'intervention' were searched in combination. Studies were differentiated based on whether measurements were taken under simulated or natural climbing conditions. Studies up until February 2014 were identified through search of MEDLINE and Embase databases. Studies that did not report perceptual or movement data during the performance of climbing tasks were excluded.
Results: Qualitative synthesis of 42 studies was carried out. Results demonstrated that skilled climbing performance is understood on the basis of: superior perception of climbing opportunities; optimised body-to-surface distancing; optimisation of fluency in movement parameters, and; a minimisation of exploratory behaviour (information gathering movements) relative to performatory movements (actions for certain goal achievement).
Conclusions: Skilled climbing involves rapidly and fluently transitioning between holds. Elite climbers exhibit advantages in detection and use of climbing opportunities when visually inspecting a route from the ground and when physically moving though a route. Perceptual and motor adaptations that improve measures of climbing fluency are highly significant for improving climbing ability level.

3.1 Introduction

Climbing is a physical activity and sport that encompasses disciplines including ice climbing (where hand held hooks and specialised footwear are used to climb ice formations), mountaineering (mountain ascent), traditional (ascent of rock faces during which the climber places and removes protective bolts), sport (ascent of artificial and natural faces, where bolts are already in place) and bouldering (low height) (detailed in Lockwood and Sparks (2013) and Morrison et al. (2010)). Each discipline can be more strictly defined into sub-categories by differences in performance location, regulations, equipment, risk and norms. For example on-sight climbing is where the climber has not physically practiced on the route but has had the opportunity to observe the route from the ground (referred to as route-preview). Whereas, red-point climbing refers to when the individual has physically practiced on a route. Other common permutations include ‘leading’, which refers to when the climber secures their ascent at set points throughout the route by securing a safety rope, fitted to a harness worn at the hips, to bolts on the wall. Top-rope climbing means the rope is passed through a clip at the top of the route prior to undertaking the ascent and there is no need to secure the ascent during the climb. Because of the extensive range of climbing disciplines, a common goal in climbing is to improve performance in intended contexts (such as a competition or outdoor environment) through experience under training conditions (such as in an indoor training gym).

Climbing performance can be understood from different scientific disciplines and has been reviewed from the perspectives of injury risk (El-Sheikh, Wong, Farrokhyar, & Thoma, 2006; Haas & Meyers, 1995; Holtzhausen & Noakes, 1996; Morrison et al., 2010; Nelson & McKenzie, 2009; Peters, 2001; Rooks, 1997; Schöffl & Schöffl, 2006, 2007; Windsor, Firth, Grocott, Rodway, & Montgomery, 2009), testing (Draper, Canalejo, et al., 2011; Robertson, Burnett, & Cochrane, 2014), physiology and anthropometry (Giles, Rhodes, & Taunton, 2006; Sheel, 2004), strength and conditioning (K. C. Phillips, Sassaman, & Smoliga, 2012), health (Buechter & Fechtelpeter, 2011) and engineering design

(Fuss & Niegl, 2010b; Smith, 1998). Currently, only isolated aspects of climbing skill performance have been the focus of previous discussion (coordination of hand-hold interactions (Fuss & Niegl, 2006b, 2012) and pedagogical approaches, (Davids, Brymer, Seifert, & Orth, 2014; Fleming & Hörst, 2010)) and a comprehensive review pertaining to coordination and it's acquisition in climbing is needed.

Traditionally, in climbing, factors that affect performance are reduced to a one-dimensional grade value, such as the French Rating Scale of Difficulty (F-RSD) used extensively in Europe, Yosemite Decimal System (YDS) used in the United States and Ewbank System common to Australia, New Zealand and South Africa. These rating scales are used to classify route difficult and ability level of the climber (Draper, Canalejo, et al., 2011). The F-RSD, for example, is an alpha-numeric value ranging from 1 to 9b+ where, according to Draper et al. (2011), a male is considered elite if he successfully climbs a route graded between 8a+ to 8c+ (with three intermediate steps). Rating scales are meaningful as a general training aid and for experimental purposes (for example, Table 3.3 shows how scales can be converted to statistically usable, number only systems such the Ewbank and Watts scales). In reality, as Draper et al. (2011) highlight, an extensive range of factors can affect climbing performance including the nature of skilled behaviours used during climbing.

Table 3-3. Examples of current rating scales and their relationships used to classify route and ability level of climbers.

Ability group	French Rating Scale of Difficuly		Yosemite Decimal System		Ewbank		Watts	
	male	female	male	female	male	female	male	female
Lower grade	1	1	5.1	5.1	9	9	0	0
	…	…	…	…	…	…	…	…
	5	5	5.9	5.9	17	17	0.75	0.75
Intermediate	5+	5+	5.10a	5.10a	18	18	1.00	1.00
	…	…	…	…	…	…	…	…
	7a	6b+	5.11d	5.11a	23	22	2.50	2.00
Advanced	7a+	6c	5.12a	5.11b	24	22	2.75	2.25
	…	…	…	…	…	…	…	…
	8a	7c	5.13b	5.12d	29	27	4.00	3.50
Elite	8a+	7c+	5.13c	5.13a	30	28	4.25	3.75
	…	…	…	…	…	…	…	…
	8c+	8b+	5.14c	5.14a	34	32	5.25	4.75
Higher Elite	9a	8c	5.14d	5.14b	35	33	5.50	5.00
	…	…	…	…	…	…	…	…
	9b+	9b+	5.15c	5.15c	38	38	6.25	6.25

Note: Adapted from Draper et al. (2011).

From a skill acquisition, understanding climbing performance is based on how effectively individuals coordinate perceptual and motor behaviour to meet performance demands (Seifert, Button, & Davids, 2013). The measurement of coordinated behaviours are predicated on patterned relationships between relevant limbs and body segments that emerge from perception of information from a performance environment (Seifert, Button, et al., 2013). In climbing, functional coordination patterns emerge from the perception and use of information during route preview and climbing to complete a route safely, quickly and efficiently (Boschker, Bakker, & Michaels, 2002; Cordier, Mendès-France, Pailhous, & Bolon, 1994; Davids et al., 2014; Seifert, Wattebled, et al., 2013). During route preview climbers visually inspect a route from the ground to consider how to coordinate their actions with respect to important surface features and properties (Boschker et al., 2002; Pezzulo, Barca, Bocconi, & Borghi, 2010; Sanchez, Lambert, Jones, & Llewellyn, 2012). During performance, individuals coordinate their actions with respect to features of the climbing surface by forming coordinated relationships between limbs (Seifert, Coeurjolly, Hérault, Wattebled, & Davids, 2013) and surface properties (Fuss & Niegl, 2008a; Zampagni, Brigadoi, Schena, Tosi, & Ivanenko, 2011), which are regulated over time to complete the route (Cordier, Mendès-France, Bolon, & Pailhous, 1993). Specific measures can, therefore, include: forces applied at hand-holds (Bourdin, Teasdale, & Nougier, 1998b; Fuss & Niegl, 2008a), limb (Seifert, Coeurjolly, et al., 2013) or whole body kinematics (Cordier, Mendès-France, Pailhous, et al., 1994; Sibella, Frosio, Schena, & Borghese, 2007; Zampagni et al., 2011), gaze position (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008), cognitions and perceptions (Boschker & Bakker, 2002; Pezzulo et al., 2010; Seifert, Wattebled, et al., 2014) made during climbing tasks.

The acquisition of coordination, at a general level, involves adaptations in the structural and functional characteristics of an individual to the factors that influence behaviour during practice (Glazier & Davids, 2009). Additionally, the transfer of skills to performance contexts which differ from practice environments is highly dependent on prior experience and the level of expertise developed (Issurin, 2013; Rosalie & Müller, 2012; Seifert, Wattebled, et al., 2013). The constraints-led approach (Newell, 1986, 1991, 1996) has proven a powerful and multi-disciplinary framework for identifying important factors, and their potential interactions, that can influence coordination processes during performance, practice and development (Chow, Koh, Davids, Button, & Rein, 2014; Davids, Glazier, Araújo, & Bartlett, 2003; Glazier & Davids, 2009; Lee, Chow, Komar, Tan, & Button, 2014; E. Phillips, Farrow, Ball, & Helmer, 2013). For example, interacting constraints on climbing behaviours include the individual (e.g. arm-span, fingertip strength and recovery (Philippe, Wegst, Müller, Raschner, & Burtscher, 2012)), the task (required speed (Rosponi, Schena, Leonardi, & Tosi, 2012), lead versus top-rope (Hardy & Hutchinson, 2007)) and the environment (wall slope (de Geus, O'Driscoll, & Meeusen, 2006), hold characteristics (Fuss & Niegl, 2012)). These constraints mutually interact during performance to place boundaries on an individual's coordination behaviours (Glazier & Davids, 2009) (these ideas are summarised in Figure 3.1 below).

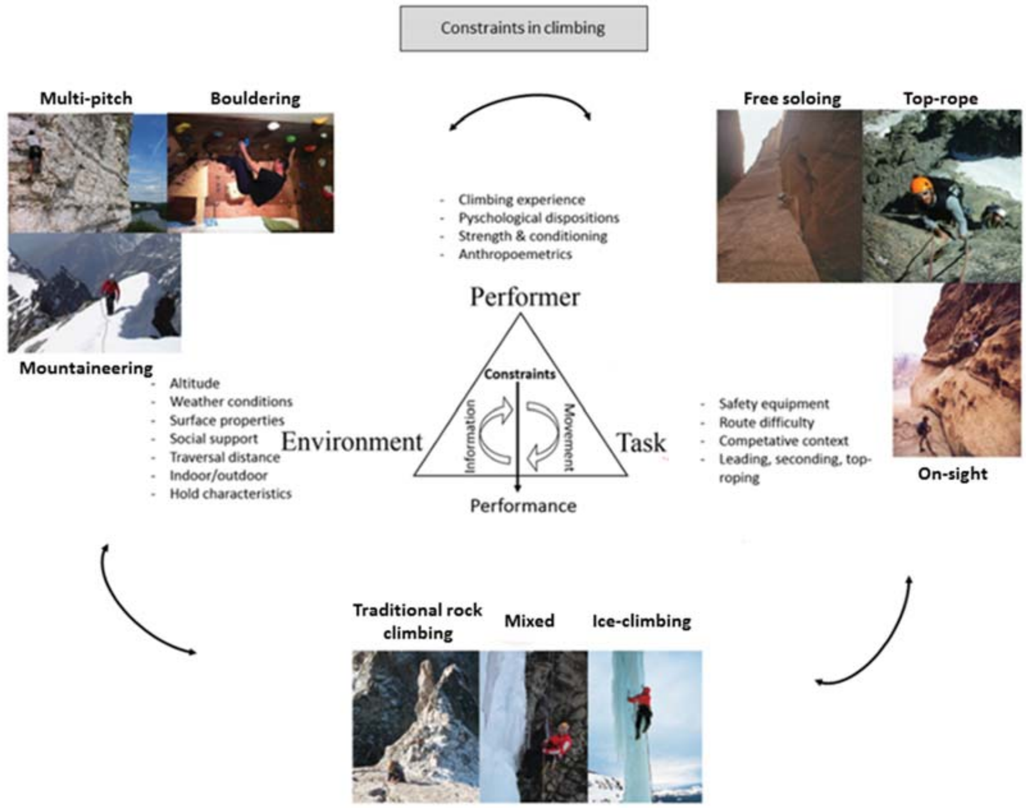

Figure 3-1. Interactive characteristics of constraints on coordination in climbing.

From an experimental perspective, coordination can be understood through four broad approaches. First, observing the coordination behaviours of expert individuals who, through extensive experience and practice, have adapted unique characteristics that enable them to perform under exceptionally difficult levels of constraint (Ericsson, Charness, Feltovich, & Hoffman, 2006) (such as competition, (Sanchez, Boschker, & Llewellyn, 2010) or extreme environments (Seifert, Wattebled, et al., 2014)). Second, contrasting coordination behaviours of performers, based on expertise level (Draper, Dickson, Fryer, & Blackwell, 2011), can determine behaviours that can be developed through training or feedback (Hodges & Williams, 2012; Sigrist, Rauter, Riener, & Wolf, 2013) (such as in recently published articles (Fryer et al., 2012; Fuss & Niegl, 2008a; Sanchez et al., 2012; Seifert, Wattebled, et al., 2014; Zampagni et al., 2011)).Third, practice effects also provide insights into how coordination evolves and what factors influence the rate, retention and transfer of skill acquisition (Newell, 1996;

Ranganathan & Newell, 2013; Schmidt & Lee, 2011; Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009). Finally, coordination and it's acquisition can be understood by observing the effect of manipulation different environmental and task constraints (such as changing hand-hold characteristics (Fuss, Weizman, Burr, & Niegl, 2013; Nougier, Orliaguet, & Martin, 1993)).

This review provides an overview of how coordination in climbing can be studied at the level of the interactions of each individual and a performance environment, considering the role of interacting constraints on emergent behaviours. The first step in approaching this task was to uncover the existing data from observation of emergent perceptual and/or motor behaviours during actual or simulated climbing tasks. Studies were next considered in terms of observations based on: elite climbers; skill differences; the effect of practice, and; the impact of scaling constraints. Sources are integrated by common topics that emerged and conclude by identifying future research priorities.

3.2 Methods

3.2.1 Search strategy

MEDLINE and Embase databases were searched for published primary sources. Key words for climbing were pooled via Boolean operation 'OR' (including: rock, ice, mountaineering, bouldering, artificial, top-rope, lead-rope, speed, mixed, indoor, outdoor, preview, route finding, slope) and combined with 'climbing' (via 'AND'); and then combined via 'AND' with pooled key words related to skill (skill, transfer, performance, ability, expertise, novice, intermediate, advanced), measures of interest (dynamic, force, kinematics, kinetics, perception, action, cognition, behaviour, centre of mass, recall, gaze, vision, motor, coordination, feet, hands, grasp, movement pattern) and intervention (intervention, pedagogy, feedback, constraint, coaching, learning, practice). Full texts from the earliest available record up until February 2014 were retrieved and citations were scrutinised by hand for additional studies.

3.2.2 Inclusion criteria, data extraction and management

Primary inclusion criteria, required studies measure perceptual, spatial and/or temporal characteristics of the climber during interactions with a wall surface during an ascent or, during, or immediately following, preview of a route, and significance of outcomes were interpreted as either positive, neutral or negative for performance based on the authors of the identified studies. A secondary criterion was that the task needed to involve a route that was theoretically gradable according to an existing climbing discipline. Data on sample characteristics, nature of interventions, task, observations and significant effects reported by study authors were extracted and stored in summary tables. Studies not reported in the English language, or an unverifiable source, were excluded.

3.3 Results

A total of 190 articles were located through data base searching (n = 145) and scrutiny of reference lists (n = 45). After duplicate removal (n = 24), 166 article titles and abstracts were screened, leaving a total of 63 articles which were assessed for eligibility using the inclusion criteria. Articles (n = 21) were excluded with reason and qualitative synthesis of the consequent 42 studies was carried out (see Figure 3.2 below for an overview of the selection process).

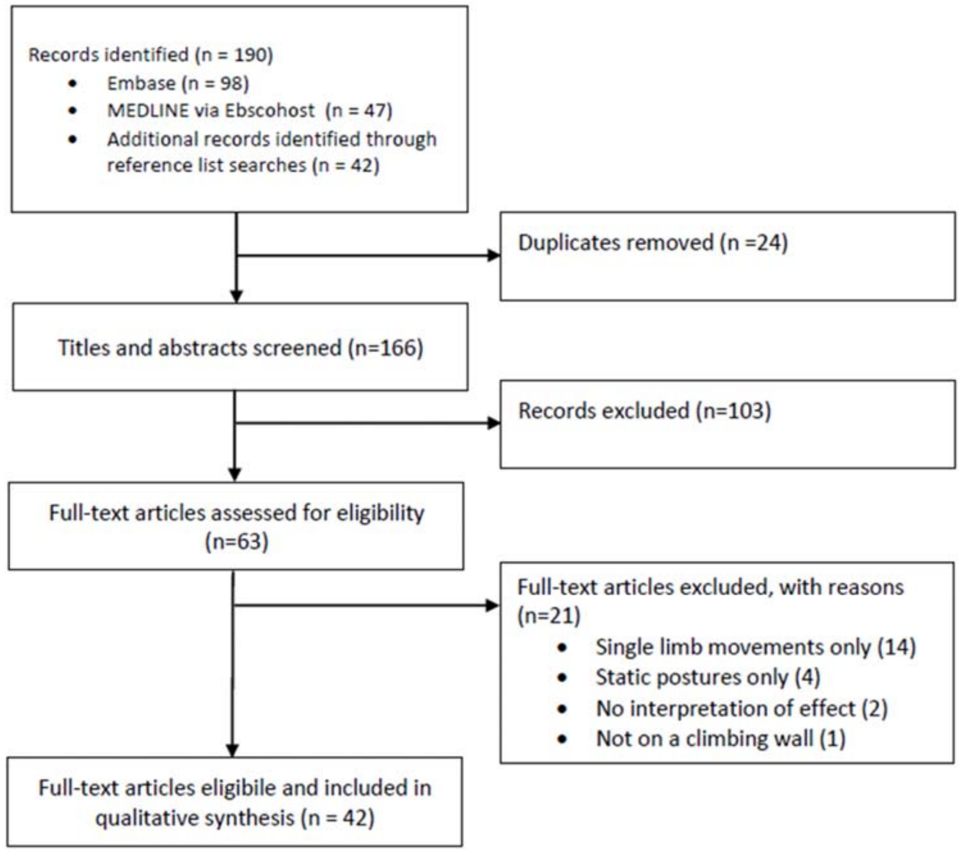

Figure 3-2. Flowchart of the selection process for inclusion of articles in the systematic review.

Using the grouping criteria developed, it was found that studies could be identified to have evaluated the effects of: 1) elite climbers (determined as per categories outlined by Draper and colleagues (Draper, Canalejo, et al., 2011)): (Fuss & Niegl, 2008b, 2010a; Sanchez et al., 2010; Zampagni et al., 2011); F-RSD for ice-climbing = 6-7, a scale that ranges between 1-7: (Seifert, Wattebled, et al., 2014), and; World Cup ranking under 50: (Fuss & Niegl, 2008a; White & Olsen, 2010); 2) ability level (twenty-six studies (Boschker et al., 2002; Cordier, Dietrich, & Pailhous, 1996; Cordier, Mendès-France, Bolon, & Pailhous, 1994; Cordier, Mendès-France, Pailhous, et al., 1994; Fleming & Hörst, 2010; Fryer et al., 2012; Fuss, Burr, Weizman, & Niegl, 2013; Fuss & Niegl, 2006a, 2008a, 2008b, 2010a; Fuss, Weizman, et al., 2013; Ladha, Hammerla, Olivier, & Plötz, 2013; Lechner, Filzwieser, Lieschnegg, & Sammer, 2013; Pansiot, King, McIlwraith, Lo, & Yang, 2008; Pezzulo et al., 2010; Russell, Zirker, & Blemker, 2012; Sanchez et al., 2010; Sanchez et al., 2012; Seifert, Coeurjolly, et al., 2013; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, L'Hermette, & Herault, 2011; Seifert, Wattebled, et al., 2013; Sibella et al., 2007; White & Olsen, 2010; Zampagni et al., 2011)); 3) practice (eleven studies (Boschker & Bakker, 2002; Boschker et al., 2002; Cordier et al., 1996; Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994; Fleming & Hörst, 2010; Fuss & Niegl, 2008a; Pansiot et al., 2008; Seifert, Orth, et al., 2014; Seifert, Orth, Herault, & Davids, 2013)), and; 4) environmental (twelve studies (Billat, Palleja, Charlaix, Rizzardo, & Janel, 1995; Fuss & Niegl, 2008b, 2010a; Fuss, Weizman, et al., 2013; Nieuwenhuys et al., 2008; Oono, Kitamura, Nishida, & Motomura, 2013; Pijpers, Bakker, Oudejans, & Boschker, 2001; Pijpers, Oudejans, & Bakker, 2005; Pijpers, Oudejans, Bakker, & Beek, 2006; Pijpers, Oudejans, Holsheimer, & Bakker, 2003; Seifert, Orth, et al., 2014; Seifert, Orth, et al., 2013)) and/or task factors (twelve studies (Boschker & Bakker, 2002; Draper, Dickson, et al., 2011; Fuss & Niegl, 2006a, 2008a; Green, Draper, & Helton, 2014; Green & Helton, 2011; Grushko & Leonov, 2014; Hardy & Hutchinson, 2007; Pansiot et al., 2008; Pezzulo et al., 2010; Pijpers et al., 2006; Sanchez et al., 2012)). Fifteen studies (Amca, Vigouroux, Aritan, & Berton, 2012; Bourdin, Teasdale, & Nougier, 1998a; Bourdin et al., 1998b; Bourdin, Teasdale, Nougier, Bard, & Fleury, 1999; Noé, 2006; Nougier et al., 1993; Pijpers et al., 2006; Quaine & Martin, 1999; Quaine, Martin, & Blanchi, 1997a, 1997b; Quaine, Martin, Leroux, Blanchi, & Allard, 1996; Robert, Rouard, & Seifert, 2013; Testa, Martin, & Debu, 1999; Testa, Martin, & Debû, 2003) did not fulfil secondary criteria. Studies fulfilling primary criteria were then organised according to general and climbing specific constraints to identify substantive themes in the literature (refer to Table 3.4 for an overview).

Table 3-4. Characteristics of constraints on climbing task uncovered through review procedure. Example studies are referenced throughout.

Constraint	General	Specific
Task	Instruction	Required climbing speed (Pijpers et al., 2005); use specific gripping technique (Boschker & Bakker, 2002), reaching action (Bourdin et al., 1998a), postural position (Bourdin et al., 1998b) and/or movement pattern (Zampagni et al., 2011); attend to additional foci (Green et al., 2014); self-preferred (Russell et al., 2012); competition event (Sanchez et al., 2010); apply a maximal force (Amca et al., 2012).
	Route safety demands	Lead-roped (existing bolts) (Hardy & Hutchinson, 2007); top-roped (Pijpers et al., 2006); bouldering (safety mats, no-rope) (White & Olsen, 2010); roped.
	Route practice	On-sight (Sanchez et al., 2010) 2nd attempt (Fleming & Hörst, 2010); after practice (Cordier et al., 1993).
	Route preview	With preview (Sanchez et al., 2010); without preview (Sanchez et al., 2012); flash (demonstration by a peer) (Boschker & Bakker, 2002).
	Specialised equipment	Ice tools (Robert et al., 2013).
	Outcome performance objective	Competition (White & Olsen, 2010); best time possible (Fuss & Niegl, 2006a); memory recall (Boschker et al., 2002); attempt to complete route (no other specific instruction) (Seifert, Orth, et al., 2013); movement simulation (Zampagni et al., 2011); estimate behavioural opportunities (Pezzulo et al., 2010); route find (visual) (Grushko & Leonov, 2014).
	Difficulty level	Very easy; lower grade; intermediate; advanced; elite; set relative to climber's ability (Pezzulo et al., 2010).
Env.	Route properties	Artificial (Seifert, Orth, et al., 2014), ice (Seifert, Wattebled, et al., 2013), rock (Fleming & Hörst, 2010).
	Weather	Indoors (Seifert, Orth, et al., 2014); outdoor.
	Context	Competition (White & Olsen, 2010); climbing gym (Pansiot et al., 2008); natural surface (Seifert, Wattebled, et al., 2013); specialised laboratory surface (Amca et al., 2012).
	Wall	Slope (Noé, Quaine, & Martin, 2001); height (Pijpers et al., 2006).
	Holds	Number of edges (Seifert, Orth, et al., 2014); edge depth (Fuss, Weizman, et al., 2013); shape complexity (Billat et al., 1995).
	Route design characteristics	Horizontal and vertical inter-hold distances (Pansiot et al., 2008), crux points (Seifert, Orth, et al., 2013), continuous difficulty (Seifert, Wattebled, et al., 2011), escalating difficulty within route (Boschker et al., 2002), rest points (Fryer et al., 2012).
Ind.	Psychological	Anxiety (Hardy & Hutchinson, 2007).
	Ability level	No experience (Boschker & Bakker, 2002); lower grade (Seifert, Wattebled, et al., 2013); intermediate (Sanchez et al., 2012); advanced (Boschker et al., 2002); elite (Zampagni et al., 2011).
	Structural and functional	Anthropometric (Pansiot et al., 2008; Sibella et al., 2007).
	Developmental	Age (Testa et al., 2003); Previous Climbing Genres (Seifert, Wattebled, et al., 2013).

3.4 Discussion

3.4.1 Characterising elite climbing skills

Elite climbers have been observed in: competitive on-sight, lead-rope (Fuss & Niegl, 2008a; Sanchez et al., 2010) and bouldering contexts (White & Olsen, 2010); top-roped, submaximal ice-climbing (Seifert, Wattebled, et al., 2014); top-roped laboratory conditions (Zampagni et al., 2011), and; in an isolated movement problem (Fuss & Niegl, 2010a).

3.4.1.1 Coordination of posture when reducing the area of support

Research has shown that postural constraints are major factors driving adaptations in the static and dynamic coordination behaviours of climbers. A climber's postural stability is constantly under threat because, the available surface area over which to support body-mass is limited (Bourdin et al., 1998a, 1998b). This challenge can be further compounded by a surface slope (Noé, 2006; Noé et al., 2001), relative sizes of (Bourdin et al., 1999) and distances between supports (Nougier et al., 1993). When transition from a static four-limb support coordination mode to a three-limb support mode is required (Quaine & Martin, 1999; Quaine et al., 1997a), climbers maintain postural stability through anticipatory redistributions in weight, supporting adaptations to the slope (Noé, 2006; Noé et al., 2001), hold size (Nougier et al., 1993; Testa et al., 1999; Testa et al., 2003), hold distribution (Nougier et al., 1993; Testa et al., 1999; Testa et al., 2003) and initial posture (Nougier et al., 1993; Quaine et al., 1997b).

In transitioning from a static to dynamic state, when a new surface hold must be grasped, this threat to postural stability also shapes the emergence of coordination of the reaching action where an emphasis is placed on movement preparation to reduce the amount of time spent in the three-limb coordination mode (Bourdin et al., 1998a). This is also the case when the size of the hold is reduced (Bourdin et al., 1998b). When multiple reach and grasp movements are organised sequentially (Bourdin et al., 1998a, 1998b; Bourdin et al., 1999), movement time continues to be faster, even if hold size is reduced (Bourdin et al., 1998b) but, additionally, attentional demands during regulation of the terminal phase of the first reach and grasp action are increased (Bourdin et al., 1998a) suggesting that actions required later in a movement sequence influence the climbers cognitions during current activity.

Supporting these findings, White and Olsen (2010) undertook a time-motion analysis of elite climbers during a national bouldering competition, revealing a minimisation of time spent reaching to grasp holds, relative to other states. Specifically, in trials that took on average 29.8 seconds (SD = 1.7): 22.3 seconds (SD = 2.1) were spent in a dynamic state (being in contact with a hold at the same time as a hip movement emerged); 7.5 seconds (SD = 1.6) were spent in static mode (in contact with a hold but with no hip movement), and they reported only *0.6* seconds (SD = 0.1) were spent reaching for holds. Considering the large amount of time spent in static and dynamic states (similar to (Billat et al., 1995)), the specific coordination behaviours exhibited during these organisational states should have an important role in climbing performance. For example, although more experienced climbers can spend similar amounts of time in static states, compared to less experienced climbers, this time has reportedly involved more active resting (shaking the wrist or chalking) (Fryer et al., 2012).

3.4.1.2 Coordination of actions when climbing through a route

Zampagni et al. (2011) investigated whether adapted coordination strategies emerge during continuous climbing, comparing centre of mass (COM) positioning and hand-hold reaction forces of a group of experienced climbers (advanced-elite) relative to a group of inexperienced climbers. Participants top-roped a wall made up of large, uniform holds (13 cm height x 16 cm width x 12 cm depth), arranged in two parallel vertical columns (separated 50 cm horizontally and 57 cm vertically). They were instructed to climb using the same coordination sequence to pass between holds and maintain a tempo of 4 seconds per climb cycle (one climbing gait cycle corresponded to a right foot lift-left foot and trunk lift-right hand lift-left hand lift). Experienced climbers exhibited a significant tendency to keep the COM further from the wall during both static and dynamic climbing phases and displayed larger lateral oscillations in COM position when taking new holds (Zampagni et al., 2011). It was suggested that a far position from the wall would require less organisation by the nervous system for regulating counterbalancing torques and, that an improvement in joint mobility would be gained from this approach. It was also suggested that, by oscillating laterally the COM, climbers exploit mechanical energy to take advantage of more efficient force/length relationships in muscles (Zampagni et al., 2011).

Russel et al. (2012) also addressed how climbers coordinated posture with surfaces, suggesting that by positioning the COM further from the wall, climbers were able to maintain an arm-extended position for longer during vertical displacement. In experienced climbers (intermediate level), this coordination mode resulted in a more functional force-length relationship in the biceps brachii (a flexor). Conversely, the more flexed arm positions adopted by inexperienced climbers favoured the use of triceps brachii (an extensor). Although total work was the same between the adapted postures, the experienced climbers tended to minimise the magnitude of the force generated relative to their own maximum force generating capacity, whilst inexperienced climbers minimised the magnitude of the overall force (Russell et al., 2012). Similarly, in static postural tasks, skilled climbers have been shown to evenly distribute forces across hand holds when coordinating self-preferred postures compared to experimenter-imposed arm flexed positions (Russell et al., 2012). These studies suggest that for estimating the efficiency of a climber’s static and dynamic movements, the angular magnitudes at the elbow joints can provide useful information. Importantly however, the instructions in the study of Russell et al. (2012) differed to those imposed on participants by Zampagni et al. (2011), not constraining the sequencing of movements in the climbing cycle. As a consequence, different climbing cycle patterns were spontaneously coordinated. However, the impact of different climbing gaits were not tested (Russell et al., 2012). Additionally, limitations proposed in both studies (Russell et al., 2012; Zampagni et al., 2011) were that hold characteristics were very easy relative to the ability level of the participants. It is feasible that hold configurations and sizes encountered under more challenging constraints may not permit 'optimisation' of arm or body positions to be coordinated (e.g. (Amca et al., 2012; Bourdin et al., 1999; Nougier et al., 1993)), requiring different coordinated behaviours.

Indeed, Fuss and Niegl (2008a; 2013) highlight contrasting results showing that, to increase friction at a hold surface, climbers can only reduce tangential force by moving their COM closer to the wall. Fuss and Niegl (2010a) and colleagues (2013) also evaluated reaction forces during dynamic climbing. In their study, participants with a range of ability levels (including an elite climber) were required to jump and grasp a hold scaled across six different vertical heights. Successful attempts involved jumping higher than necessary to complete the hold and grasping it before the dead point (where the COM transitions to returning to the ground). Increasing the distance of the COM from the wall during this technique had the effect of increasing the hip angle, reducing the effective height of the climber, signifying that a higher jump was needed to reach the hold. Fuss and colleagues (2013) also examined how the slope of a hold, when systematically reduced from the horizontal, influenced coordination of hold forces. At specific values, a transition from applying horizontal pulling forces at the hold to applying horizontal, pushing forces to use the hold was exhibited (22° from the horizontal in less experienced individuals, and 34° in more experienced climbers). The latter coordination strategy indicated that the hips were moving away from the wall in a qualitatively different manner in order to use the hold at the more extreme angles (Fuss, Weizman, et al., 2013).

3.4.1.3 Rate of adaptation to environmental constraints

Of interest in understanding expertise is coordination of forces at hand-holds and how these can contribute to climbing performance. Fuss and Niegl (2008a) evaluated time series of reaction forces applied to a handhold equipped with 3-D piezoelectric transducers during on-sight lead competition ascents and compared mechanical parameters. In the first experiment, three functional phases of hold interactions were highlighted (Fuss & Niegl, 2008a). The first phase corresponded to a 'set-up' phase where resultant force variability was considered as haptic exploration to position the fingers and hand. The 'crank' phase involved applying force for the purpose of lifting the COM. Finally, the 'lock-off' involved a combined period where load was transferred to another limb at the same time as the hand began to move to another hold (see Figure 3.3, modified from Fuss and Niegl (2008a)).

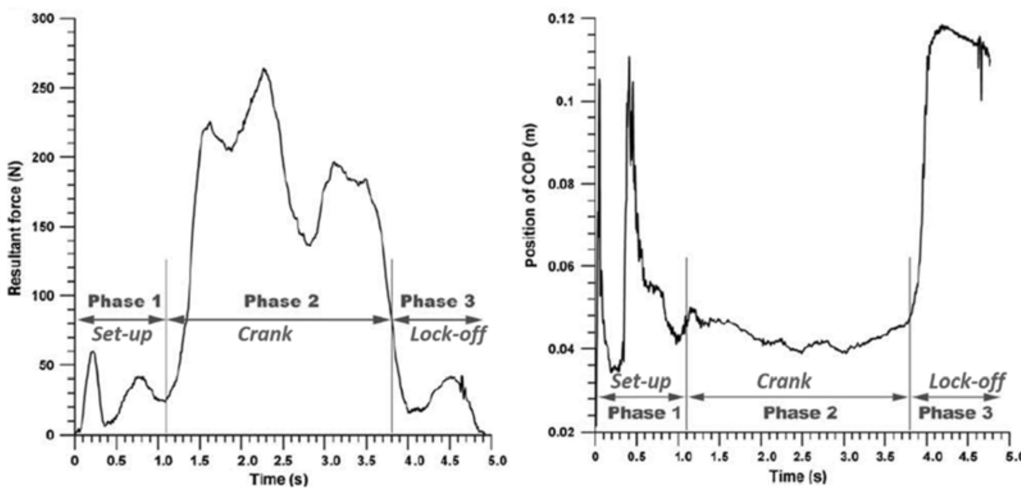

Figure 3-3. Three phases of hold regulation. **N** = Newtons, **COP** = centre of pressure, **s** = seconds.

In experiment 2 Fuss and Niegl (2008a) compared a lower ranked climber (World Cup ranking of >50) with an elite counterpart (World Cup ranking of <20) on the different phases of contact (set-up, crank, lock off, see Figure 3.3). The lower ranked climber spent a longer period in set-up as well as exhibiting a prolonged lock-off phase. In fact, this climber also fell due to an inability to organise a high enough friction coefficient (Fuss & Niegl, 2008a). In contrast, the set-up phase for the more experienced individual was almost non-existent, suggesting that the climber was either in a better position to immediately use the hand hold, or, had an advanced understanding of how to use the hold, not requiring exploratory behaviour.

A reduction in parameters that measure overt exploratory behaviour in elite climbers has also been revealed at the limb level by Seifert and colleagues (2014). Elite ice-climbers climbing a moderately difficult route (F-RSD for ice-climbing = level 5+) were evaluated on parameters related to exploration and sources of information relied upon. Multi-modal sources were found to contribute to coordination of action (see also Smyth and Waller (1998)). Specifically, elite climbers reported the relationships between structural features of the climbing surface and behavioural opportunities were located through visual search and through auditory (sounds of hook-ice interactions) and haptic perception (vibration) (Seifert, Wattebled, et al., 2014). These informational constraints emerged in conjunction with performance data showing continuous vertical ascent and a 1:1 ratio in ice-hook swinging relative to implementing definitive anchorages. In contrast, inexperienced ice-climbers displayed very slow ascent rates and a ratio of about three swings to every definitive anchorage, suggesting an inability to perceive climbing opportunities for ascent support in an ice-fall (Seifert, Wattebled, et al., 2014). These less experienced individuals also reported that their search was primarily visual and pertained to structural features of the ice surface (such as size of holds).

3.4.1.4 Psychological and behavioural relationships to climbing performance

Psychological factors are an important individual constraint in climbing (Aşçi, Demirhan, Koca, & Dinc, 2006; Draper, Jones, Fryer, Hodgson, & Blackwell, 2008; Draper, Jones, Fryer, Hodgson, & Blackwell, 2010; Feher, Meyers, & Skelly, 1998; Fryer, Dickson, Draper, Blackwell, & Hillier, 2013; Hodgson et al., 2009; Maynard, MacDonald, & Warwick-Evans, 1997; Sanchez et al., 2010) and their impact on coordination behaviours has been previously raised (de Geus et al., 2006; Draper, Dickson, et al., 2011; Green et al., 2014; Llewellyn & Sanchez, 2008; Llewellyn, Sanchez, Asghar, & Jones, 2008), although rarely measured directly. Sanchez et al. (2010) reported movement data captured during a climbing championship for the same on-sight lead climb. Frontal plane geometric index of entropy (GIE) and climb times were analysed at the first two sections of a three section route and at two crux points (crux points refer to parts of a climb that are more difficult than the overall average). GIE provides a measure of how 'chaotic' a movement trajectory is and measures indicate the fluency of a curve, where: the higher the entropy, the higher the disorder of the system, whereas; a low entropy value is associated with a low energy expenditure and greater climbing fluency. Sanchez et al. (2010) found that better performance outcomes correlated positively with high levels of somatic anxiety, but only in combination with positive affect. More expert climbers also showed slower climb times within a crux point. Whilst no relationships between performance outcomes and GIE were found, an association between pre-performance emotions and GIE was reported. Similar to data reported by Pijpers and colleagues (2001; 2003) involving inexperienced climbers, higher anxiety appears to increase entropy during climbing.

Similarly, Hardy and Hutchinson (2007) assessed climbers' performance using the Climbing Performance Evaluation Inventory (CPEI). Specially, the CPEI is relevant in this discussion because it includes ratings on efficiency in equipment use, gracefulness in movement, economy of effort, ability to read the route and levels of focus and control. Using these measures, Hardy and Hutchinson (2007) showed that anxiety induced by leading at the limit of ability can have a detrimental effect on performance. However, if climbers perceived experienced anxiety in a positive way, they did not show performance decrements in behaviour. Draper et al. (2011) also found that climbers who successfully completed either lead or top-rope routes reported higher levels of confidence. This study also measured the time taken to reach seven successive positions in the route, showing that successful climbers tended to surpass early sections faster, compared to those who fell. Interestingly, successful climbers had a higher overall oxygen consumption, suggesting they had a reduced anabolic demand compared to climbers who fell, possibly signifying a different climbing style. Additionally, despite the overall group consisting of climbers within a similar ability level, as shown in small standard deviation data in the reported Ewbank (on-sight was 18.4±0.5 and red-point 20.7±1.1), their years of experience were significantly different (the successful groups climbing age = 4.8yrs±3, whereas the unsuccessful groups climbing age was = 2.2±0.5). This finding suggests that practice volume supports climbing performance, even if absolute ability level is no different, with data implying that behaviour and perhaps psychology of more experienced individuals during the ascent being an important factor.

3.4.2 Skill effects in climbing: Implications for understanding preview and route finding performance

As highlighted earlier, skill differences can uncover important adaptations, many of which can appear counterintuitive. Skill differences discussed in the following section pertain to preview tasks (Boschker et al., 2002; Pezzulo et al., 2010), and relationships between coordination and climbing fluency (Cordier et al., 1996; Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994; Seifert, L'Hermette, et al., 2011; Seifert, Orth, et al., 2014; Seifert, Wattebled, et al., 2013; Sibella et al., 2007).

3.4.2.1 The acquisition of climbing specific skill supports preview performance

Competition can involve on-sight climbs, and it is tacitly assumed that an ability to determine effective route planning, prior to climbing, can improve performance, however, this remains to be shown conclusively (Sanchez et al., 2012)). Boschker et al. (2002) and Pezzulo et al. (2010) raised questions related to the ability to recall information after preview, suggesting that, because climbers undertake a movement simulation during route preview, recall of the climbing route is enhanced. In both studies (Boschker et al., 2002; Pezzulo et al., 2010), climbers were required to reproduce after a viewing period, features of the climbing route (including the position (Boschker et al., 2002; Pezzulo et al., 2010) and orientation (Boschker et al., 2002) of holds). Boschker et al. (2002) compared performance across an inexperienced subgroup, a lower grade-intermediate group and an intermediate-advanced group. The advanced subgroup recalled more about the route (set at an intermediate level) and were sensitive to route properties, with their initial recall efforts based on the most difficult part of the route (the route increased in difficulty with height) (also shown in Grushko and Leonov (2014)). Less experienced climbers on the other hand, showed no particular bias to any part of the route attempting to reconstruct it in a global manner (Boschker et al., 2002). Experienced climbers also tended to simulate movements during recall, something the inexperienced climbers never did (also shown in Pezzulo et al. (2010)). When asked to verbalise what they were thinking during recall, experienced climbers primarily described usable properties, such as what grasping action or movement could be performed with holds (experiment 2) (Boschker et al., 2002). In contrast, inexperienced climbers tended to verbalise about the holds' structural features, such their shape or size (experiment 2) (Boschker et al., 2002) (similar to Seifert et al. (2014) and Pezzulo et al. (2010)). The ability to organise actions to use holds also appeared to moderate performance during preview. In support, Pezzulo et al. (2010) showed that inexperienced individuals could match the recall level of more experienced climbers when previewing an easy route that both groups could successfully climb. Furthermore, the experienced group demonstrated a significant reduction in recall performance on a route that was impossible to climb. This outcome suggests that the ability to use the route assisted recall when movement opportunities were perceived and that new movement opportunities were acquired through experience.

3.4.2.2 Skill can be predicted across a range of coordination variables that support fluency

Incorporating multiple types of coordination variables into performance analysis may also be an important approach for understanding climbing skill. For example, Sibella et al. (2007) described two types of traversal strategies: agility and power. In an individual analysis, a climber who adopted a power strategy showed higher GIE (less fluency), tended to use less than four holds at a time, and displayed larger average hip acceleration and variability. According to Sibella et al. (2007) this constellation of outcome variables seemed to emerge because the climber had not developed advanced coordination skill. Similarly, Seifert et al. (2013) showed that specific characteristics of acquired coordination patterns support performance fluency (see also Boschker and Bakker (2002)). Seifert et al. (2013) tested transfer of experienced rock climbers and inexperienced rock climbers to an unfamiliar ice-climbing environment. Climbing fluency, defined in terms of continuous vertical displacement, was related to an ability to use a repertoire of inter-limb coordination patterns that were unavailable to the inexperienced group. These differences in coordination acquisition supported a minimisation of prolonged pauses and an ability to use existing features of the ice-wall to achieve anchorage (shown in a lower ratio of ice-tool swinging to definitive anchorages) (Seifert, Wattebled, et al., 2013).

3.4.3 Practice effects in climbing: Implications for understanding the impact of intervention in the rate of learning

A major limitation of expert-novice comparison approaches is the lack of knowledge of how functional adaptations are acquired and often assumed that they are gained through a practice volume effect. However, understanding issues such as, the role of existing skill level on transfer (Seifert, Wattebled, et al., 2013), how or why new coordination modes emerge, or the impacts of interventions and pedagogical strategies (Boschker & Bakker, 2002), need to be approached by observing coordination behaviours over practice and learning timescales.

3.4.3.1 Exploration and practice improves fluency

A common observation in less experienced climbers concerns their overt exploratory behaviours. Exploratory behaviours have been assessed in terms of touching, but not using, climbing surfaces within a route (Seifert, Orth, et al., 2014; Seifert, Orth, et al., 2013; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013), qualitative assessment of 'kinks' or 'knots' in hip trajectories (Cordier, Mendès-France, Pailhous, et al., 1994), time spent without movement to devote to visual search (Sanchez et al., 2012), visual fixations whilst stationary (Nieuwenhuys et al., 2008), and finally, periods of haptic exploration whilst in contact with a hold prior to using the hold (Fuss & Niegl, 2008a).

Practice effects suggest that exploratory behaviours reduce with practice (Cordier, Mendès-France, Pailhous, et al., 1994; Seifert, Orth, et al., 2013) whilst indicators of improved efficiency increase (Boschker & Bakker, 2002; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994; Fleming & Hörst, 2010; Fuss & Niegl, 2008a; Seifert, Orth, et al., 2014). Boschker and Bakker (2002) showed that practising under instructional constraints to use a less advanced coordination mode can still result in improved climbing fluency, and at the same levels of a more advanced technical action. This finding suggests that practice of the same movement pattern can still improve fluency despite it being less technically advanced. Whether this is true as the route difficulty increases needs to be investigated. For example a pilot study by Orth et al., (2013) showed that when routes contain crux points (particularly difficult parts of a route), the coordination of grasping actions by inexperienced climbers tend to be of a more basic action, whereas experienced climbers, show a tendency to use more advanced grasping techniques, and which may have supported performance (i.e. route completion and climbing fluency (see Figure 3.4 below).

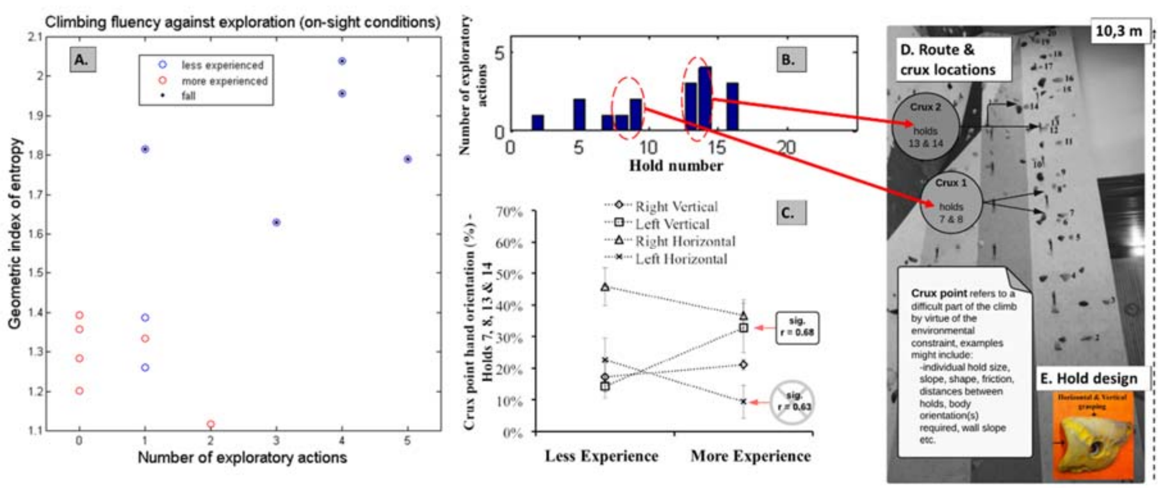

Figure 3-4. The relationship between hold difficulty and climbing behaviour.

More specifically, these data adapted from Orth et al. (2013) presented in Figure 3.4 involved 6 individuals at an intermediate level and 7 at a beginner level. Panel A of Figure 3.4 shows climbing fluency plotted against exploratory actions in skilled (red markers) and less skilled individuals (blue markers). Falls are shown by filled in circles and suggest that high exploration and entropy may be related to falls. Panel B shows the instances of exploratory behaviour relative to specific holds set within the route corresponded with crux holds. Panel C shows the relationship between the grasping action used and skill level at crux holds with less experienced climbers showing significantly more right handed overhand actions. Panel D show the route design involving 20 graspable holds and two crux regions. Panel E shows the nature of the holds designed into the route, each with graspable edges along the horizontal and vertical orientations.

Boschker and Bakker (2002) also demonstrated that a group of beginners who were shown (and instructed) on how to use an advanced coordination pattern, immediately displayed better climbing fluency compared to groups that were not shown the pattern. It seems important, however, to note that, despite practice, the control group in this study, who were instructed to climb as they liked, never began to use the advanced coordination pattern. This finding suggests that pedagogical intervention plays an important role in assisting individuals to find new skills and can increase the rate of improvement in performance. In this respect, Seifert et al. (2013) showed a relationship between exploration of new climbing actions and modification in technique (pinch gripping as opposed to overhand grasping) that appeared dependent on the nature of the route design. In Seifert et al. (2013) holds were designed to be usable with different hand orientations, where advanced actions were more advantageous if used at crux locations. Considering the study by Seifert et al. (2013) alongside the findings reported by Boschker and Bakker (2002), it may be that, unless constraints in the design of route properties require a modification in coordination (such as reorientated reaching or grasping actions) to improve climbing fluency new or better coordination of behaviour will not be explored by the learner. This highlights the importance of route design, and potentially exploration, for the emergence of more advanced climbing technique.

3.4.3.2 Existing skills increase the rate of performance improvement and may determine whether learning opportunities are available

Cordier and colleagues (1996; 1993; 1994; 1994) provided evidence that existing skill level also improves the rate of learning under a fixed set of constraints. Cordier and colleagues (1996; 1993; 1994; 1994) showed that an advanced group of climbers reduced entropy to an asymptotic level up to four trials faster than an intermediate group climbing the same route. Exploratory behaviours were related to 'kinks' or 'knots' in hip trajectories (Cordier, Mendès-France, Pailhous, et al., 1994), increasing the global level of entropy. One reason why the more experienced group exhibited lower entropy was that the route was within their ability level (Sanchez et al., 2010). Indeed, this may also be one reason why, in extant research, when skill comparisons are made, more experienced climbers do not tend to exhibit overt exploration and display better levels of efficiency because they are not challenged to find unfamiliar movement solutions due to the relative difficulty of the task (Fuss & Niegl, 2008a; Seifert, Orth, et al., 2014; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013). For example, a recent pilot study (Grushko & Leonov, 2014) reporting on a new approach to assess preview behaviour, highlights the impact of scaling route difficulty on adaptive behaviour. In the report by Grushko and Leonov (2014), gaze position data of on-sight route preview were compared between performance on an intermediate route and an advanced route. The climbers (Moscow climbing team members) were also required to lead climb the routes after preview. Whilst all participants completed the easier route, 48% fell on the harder route. Interestingly, both fixations and preview time increased on the more difficult route. Furthermore, a qualitative difference in preview strategy was reported, highlighting how the relative difficulty of a task can substantially alter climbers' tendency to explore a route's properties in skilled individuals.

3.4.4 Task and environmental manipulations in climbing research: Implications of constraint manipulation from theoretical and applied perspectives

When combined with dynamic coordination measures, constraints manipulation can: a) decipher whether experimental and performance contexts are representative (Sanchez et al., 2012; Watts et al., 2008); b) highlight similarities and differences in behaviours between different training contexts (Billat et al., 1995; Draper, Dickson, et al., 2011; Hardy & Hutchinson, 2007; Sanchez et al., 2012; Seifert, Wattebled, et al., 2013), and; c), show how stability in performance is maintained or destabilised through observing the adapted behaviours (Fuss, Burr, et al., 2013; Fuss & Niegl, 2006a, 2008b, 2010a; Fuss, Weizman, et al., 2013; Nieuwenhuys et al., 2008; Pijpers et al., 2005; Pijpers, Oudejans, & Bakker, 2007; Pijpers et al., 2006; Pijpers et al., 2003; Seifert, Orth, et al., 2014)).

3.4.4.1 Constraint manipulation can be used to affect exploratory behaviour in climbers

Exploration from a learning perspective is an important behaviour because it can allow individuals to find new patterns of coordination and modes of regulating these acquired patterns (Chow, 2013; Newell, 1991). Pijpers and colleagues (2005; 2006) have outlined the importance of distinguishing exploration from other actions in climbing, stating that 'performatory movements are meant to reach a certain goal', while 'exploratory movements are primarily information gathering movements' (Pijpers et al., 2006). In this respect exploratory behaviours reveal a need to find behavioural opportunities because of a momentary inability to detect any that are presently desirable. However, the current research in climbing pertaining to the exploration/learning relationship is not entirely clear. On the one hand exploration has been shown to increase alongside a reduction in factors related to attention (Nieuwenhuys et al., 2008; Pijpers et al., 2005; Pijpers et al., 2006). On the other hand it has been shown to decrease with practice as performance concurrently improves, suggesting a functional relationship (Seifert, Orth, et al., 2014; Seifert, Orth, et al., 2013).

Pijpers and colleagues (2005; 2006) reported that anxiety (caused by having inexperienced individuals climb at height) can narrow attention (Pijpers et al., 2006), reducing how far individuals perceive themselves capable of reaching (Pijpers et al., 2006). Induced anxiety also led to an increase in exploratory and performatory behaviours (Pijpers et al., 2006). Nieuwenhuys et al. (2008) replicated the technique of using height to induce anxiety in inexperienced individuals and considered the impact on coordinating gaze and movement. Fixations were characterised as either performatory (when the fixation occurred during a movement) or exploratory (when the fixation occurred and the climber was stationary). Participants reduced search rate (the total number of fixations divided into the sum of the fixation durations) and showed a tendency to increase exploratory fixations relative to the number of performatory fixations. Specifically, the ratio of performatory to exploratory fixations went from 6.9±1.38:15±4.88 (low) to 8.2±2.55:23.3±10.22 (high) (increasing the number of exploratory fixations relative to performatory fixations by roughly 1 in the high condition). Furthermore, climbers also increased performatory actions (low = 21.6±2.91 versus high = 24.5±3.50), suggesting an ongoing coupling of visual motor behaviours between conditions. However, data on exploratory actions were not reported and cannot confirm this.

In contrast, Seifert and colleagues (2014) observed intermediate performers climb two separate routes graded at the same difficulty level, but which differed in hand-hold properties. One route consisted entirely of holds either with two graspable edges, or with a single graspable edge (20 holds per route). The investigators assessed jerk coefficients of the climbers' hip movements over four trials of practice and showed that only in the double-edged route, did the climbers show an initial elevation of jerk, followed by a reduction and asymptote at the same level as the other route (presumably due to the choice at each hold). This pattern also corresponded to the data on the climber’s exploratory actions (touching but not grasping holds), which reduced from 4 at the first trial to 1 at last trial in single-edged route, and 9 to 3 in the double-edged route. These findings suggesting that, through exploration, the experienced climbers determined an efficient path through the route, improving performance.

3.4.5 Future research directions

A number of biases and limitations in the literature suggest a variety of novel future directions. A large number of studies were undertaken on an indoor climbing wall, in fact, only four studies could be confirmed as occurring outdoors (Fleming & Hörst, 2010; Seifert, Coeurjolly, et al., 2013; Seifert, L'Hermette, et al., 2011; Seifert, Wattebled, et al., 2014). This differentiation of conditions clearly has influenced the material properties and specialised equipment that climbers have been tested using, which predominantly involve man-made holds, but have included ice (Seifert, Coeurjolly, et al., 2013; Seifert, L'Hermette, et al., 2014; Seifert, L'Hermette, et al., 2011; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2011; Seifert, Wattebled, et al., 2013) and rock (Fleming & Hörst, 2010). Additionally, research on climbing under top-rope conditions far outweigh studies under lead rope conditions where only five studies have involved lead rope constraints (Draper, Dickson, et al., 2011; Fuss & Niegl, 2008a; Grushko & Leonov, 2014; Hardy & Hutchinson, 2007). Additionally the vast majority of studies fail to report whether participants were given an opportunity to preview a route before trials (for exceptions see the following articles (Boschker & Bakker, 2002; Fryer et al., 2012; Grushko & Leonov, 2014; Sanchez et al., 2012; Seifert, Orth, et al., 2014)), which has recently been shown to influence climbing behaviours (Sanchez et al., 2012), suggesting a bias toward studying movement coordination in isolation from perceptual processes.

Of additional concern is that studies addressing research priorities in coordination acquisition more generally remain sparse and should be addressed as a matter of priority in climbing specific contexts. They include analysis of processes such as feedback (none could be identified), transfer of skill (only one study has (indirectly) assessed this (Seifert, Wattebled, et al., 2013)), and finally how performance evolves with practice over timescales individuals normally develop skill. For example the largest number of practice trials tested has been ten (Cordier et al., 1996; Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994), which is notably, much less than would be expected is the practice volume involved in acquiring a high level of climbing skill. Furthermore the effects of intervention have not been considered from a skill acquisition perspective with only one study to have involved independent groups during practice

(Boschker & Bakker, 2002). The remainder of studies have evaluated practice under different conditions (Boschker & Bakker, 2002; Fuss & Niegl, 2006a; Seifert, Orth, et al., 2014), hence, making it difficult to isolate the mechanisms underpinning improved performance. To address this concern practice effects using pre- and post-intervention measures of skill are needed and currently lacking in the literature.

Research developments, however, appear very promising with current technology suggesting capacity to address skill across multiple levels of analysis, including eye tracking (Grushko & Leonov, 2014; Nieuwenhuys et al., 2008), estimation of the body's motion using automatic worn sensors (Ladha et al., 2013; Pansiot et al., 2008; Schmid, Shea, Friedman, & Srivastava, 2007; Seifert, L'Hermette, et al., 2011; Seifert, Orth, et al., 2014) and instrumented holds for estimating reaction forces (Fuss, Burr, et al., 2013; Fuss & Niegl, 2006a, 2008a, 2008b, 2010a). Although few studies have adopted an integrated measurement approach, some exceptions could be found. Specifically, a number of studies have combined analysis of movement coordination data with contact forces (Aladdin & Kry, 2012; Pijpers et al., 2005; Russell et al., 2012; Zampagni et al., 2011), gaze position data (Nieuwenhuys et al., 2008) and perceptual self-report (Boschker et al., 2002; Seifert, Wattebled, et al., 2014). A major future challenge is to successfully and efficiently integrate these different methods to observe interactions of climbers and surfaces in natural performance environments.

3.5 Conclusion

In summary, skilled climbing has been broadly characterised as rapidly and fluently transitioning between holds. Elite climbers exhibit a clear advantage in detection and use of climbing opportunities when visually inspecting a route from the ground and when physically moving though a route. However, direct evidence of the coordinated use of visual information has not been reported and should be a priority. Furthermore, perceptual and motor adaptations that improve measures of climbing fluidity, in the spatial and temporal dimensions, are consistently reported in relationship to higher climbing ability level. In addition to this finding, specific hand, limb, postural and inter-wall distancing adaptations have been associated with skill. These two features of skilled climbing have been suggested to bear a relationship, where, coordination of actions such as limb activity can improve skilled performance (i.e., climbing fluidity). Future research priorities should therefore be placed on developing approaches for understanding contributions of the coordination of perceptual and motor behaviour to fluidity. Finally, with regards to learning, exploratory behaviour appears to be a potential mechanism. A hypothesis developed in this review has been that optimised exploration may improve transfer of skill. Future research should determine if interventions that improve skilled climbing behaviour can be designed by manipulating task and environmental properties on the basis that they induce exploratory activity. With such data, practitioners can be supported in how to utilise the extensive range of constraints during climbing training to induce exploration of actions that support climbing fluidity relevant to an intended performance context.

In conclusion, constraints on coordination in climbing, and effects of practice and skill level, have been considered in relation to preview and climbing tasks. Experienced climbers are able to perceptually simulate how they would climb a route using information related to opportunities for action. Simulation behaviours are based on multiple modes of information and improve the ability to remember climbing surface features and can be used by experienced climbers during performance, to enhance fluency. Forces applied to hand holds also reveal a range of behavioural adaptations and are useful for evaluating effects of modifications in hold properties. Practice effects on performance reveal a number of important characteristics that practitioners should consider when setting up learning interventions. Specifically, practitioners need to be sensitive to the potentially functional nature of exploration. Research priorities should be placed on evaluating the impact of interventions with an emphasis on understanding how new skills are acquired and what pedagogical strategies can improve the transfer of skill.

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CHAPTER 4. REVIEW PAPER 3: METHODS

Measures of fluency and intentionality reveal skilled behaviours in climbers

Table 4-1. Chapter 4 Table of contents.

Table 4-2. Chapter 4 Key points.

- Smoothness (minimization of jerk), entropy and immobility each characterize skilled climbing outcomes (broadly referred to as climbing fluidity)
- Behavioural measures including exploratory and performatory behaviour characterize a climbers intentions.
- Fluency measures, capturing spatial and temporal performance dimensions can, when integrated with performatory and exploratory measures, reveal insights into previously contradictory results, indicating reasons why certain actions might reduce fluidity and yet be functional.
- Fluent ascent and related behavioural adaptations, should in principle, be the most efficient when optimized by the individual: a key hypotheses developed in this review is that adaptations supporting fluent climbing behaviour during an ascent are more conducive to successfully climbing a route.

Abstract

Objective measures of skilled behaviours, specific to a physical activity or sport are important to develop for effectively quantifying performance and learning processes. In the sport of climbing, fluency, based on spatial-temporal patterning, has been a primary measure of skilled behaviours during performance. Recently, fluency data has been combined with measures of an individual climber's intentions, e.g., whether an action is for performance achievement or exploratory in nature, providing a comprehensive analysis why individuals undertake specific actions when climbing. This review evaluates existing measurement approaches of climbing fluency and intentions, identifies limitations and considers how measures of skilled climbing behaviour can be framed within a coherent theoretical framework. A number of task and personal constraints are identified which can influence whether climbing behaviours may be interpreted as beneficial for performance and learning. These include: an individual's skill level, route design properties (such as surface height or the presence of rest locations), tasks within the route (e.g. managing safety equipment), and environmental properties of the wall (natural vs. artificial). Future research is considered with respect to addressing the influence of interacting constraints during analysis of skilled climbing performance.

4.1 Introduction

Climbing is a physical activity and competitive sport with worldwide trends of a growing participant base, and attracting consequent research attention (e.g., http://www.climbing.ethz.ch/). Due to its increasing popularity, existing methods of behavioural analyses, specific to climbing, need to be improved in order that performance and learning processes be quantified effectively. Climbing performance can be evaluated from different disciplinary approaches. For example physiological approaches determine how individual factors such as resistance to fatigue relate to the ability level of individuals (Vigouroux & Quaine, 2006). From a skill acquisition perspective, understanding performance is based on how effectively individuals adapt perceptual-motor behaviour to meet performance demands (Seifert, Button, & Davids, 2013). For example climbing involves a broad range of conditions such on-sight or red-point climbing. On-sight climbing is where the climber has not physically practiced on the route but has had the opportunity to observe the route from the ground (referred to as route-preview) (Sanchez, Lambert, Jones, & Llewellyn, 2012), whereas, red-point climbing refers to when the individual has physically practiced on a route. It is significantly more difficult to surpass a route under on-sight conditions (Draper, Canalejo, et al., 2011), attesting to the importance of understanding how perceptual-motor mechanisms contribute to performance with respect specific arrangements of conditions in environment, individual and task related factors (collectively referred to as constraints, (Davids, Button, & Bennett, 2008)).

One of the challenges in understanding climbing performance is that the task goal does not typically require an optimization of outcomes such as to finish the route as quickly as possible. Rather, the goal of climbing is to get to the end of a route which requires a balance between efficiency of action and the accumulation of fatigue. Therefore, adaptations supporting energy efficient climbing behaviour throughout an ascent are believed to be more conducive to successfully climbing a route. Hence, from a skill acquisition perspective, the particular characteristics of climbing place an emphasis on understanding how individuals adapt to the ever changing structure of route properties. In understanding climbing specific skills, observation related to how an individual couples actions to changing environmental properties during performance are, therefore, of particular interest (Seifert, Button, et al., 2013). The characteristics of these continuous performer-environment couplings, such as their complexity, can reveal each individual's adaptations for picking up information for perceiving opportunities for traversing a route successfully (Seifert, Wattebled, et al., 2014). Measures such as these in climbing has been previously estimated by spatial-temporal indicators of *performance fluidity* (Billat, Palleja, Charlaix, Rizzardo, & Janel, 1995; Cordier, Mendès-France, Bolon, & Pailhous, 1993).

Temporal indicators of performance fluidity are designed to quantify the stoppages by each climber during performance relative to continuous climbing (Billat et al., 1995; Fryer et al., 2012; Pijpers, Oudejans, & Bakker, 2005; Pijpers, Oudejans, Bakker, & Beek, 2006; Sanchez, Boschker, & Llewellyn, 2010; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013; Sibella, Frosio, Schena, & Borghese, 2007; White & Olsen, 2010). In contrast, spatial indicators are designed to indicate efficiency of a path taken through a surface (Boschker & Bakker, 2002; Cordier, Dietrich, & Pailhous, 1996; Cordier et al., 1993; Cordier, Mendès-France, Bolon, & Pailhous, 1994; Cordier, Mendès-France, Pailhous, & Bolon, 1994; Pijpers, Oudejans, Holsheimer, & Bakker, 2003; Sibella et al., 2007). Finally, combined spatial-temporal measures can indicate the smoothness of a trajectory, for example, definable as a minimization of jerk dimensions (Seifert, Orth, et al., 2014). As a climber traverses through a route they must interpret the ever-changing structure of the surface and move accordingly, a process called 'route finding' (Cordier et al., 1993, p. 371). A climber undertaking continuous climbing using a relatively simple path through a route, and transitioning between holds smoothly is qualitatively described as exhibiting *fluent* climbing (Ferrand, Tetard, & Fontayne, 2006).

That is, fluidity, as a measure of an individual's adaptations to surface properties during route finding, globally captures skilled performance in climbing.

In order to maintain performance under different constraints, climbers use performatory and exploratory actions to maintain climbing performance (Fryer et al., 2012; Seifert, Wattebled, et al., 2013). Specifically, *performatory* and *exploratory* behaviours are used to achieve the task goals or intentions of an individual during performance (Fuss & Niegl, 2008; Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008; Pijpers et al., 2005; Pijpers et al., 2006; Sanchez et al., 2012; Seifert, Coeurjolly, Hérault, Wattebled, & Davids, 2013). Understanding intentional behaviours is of significant interest because they can be used to explain why an individual's performance might be characterized by a specific spatial-temporal pattern (Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013). For example, if a climbers explores a hold for a prolonged period of time, temporal indicators of fluency will also be affected, but will explain the underpinning reason why the individuals has stopped moving. Indicators of intentionality during climbing can be acquired by activity analysis, which is a quantification of the types of activities performed by a climber using objective criteria (Billat et al., 1995) whereby, the greater the precision these techniques achieve, the more the investigator assigns an underpinning intention to an observed behavior.

Integrating these two types of data would appear to be fruitful given that, previous research has revealed interaction effects between personal, task and environmental constraints. For example whilst, climbers can demonstrate poor climbing fluency, they can concomitantly display functional actions in response to the nature of constraints, such as by exploiting rest points designed into the route (Fryer et al., 2012). The perspective adopted in this paper is that, performance in climbing is determined by the way the route is climbed. That is, different behaviours can underpin climbing a route without falls, without stops, on-sight, after training, flash (demonstration of a peer), under artificial, sportive (natural rock with existing bolts) or traditional climbing (where temporary bolts are used and retrieved).

The aim of this review was to address the value of associating spatial and/or temporal measures of climbing performance with an activity type analysis from the skill acquisition perspective. The review is structured into two parts. First, we evaluate the existing 'state of the art' for quantifying climbing fluency along spatial and temporal estimates during an ascent. Next, activity analysis is considered in seeking to understand how these measures can be related to climbing fluency. Perspectives underpinned by complex systems approaches are provided throughout the paper to show how the integration of these analytic approaches can open up new research directions for understanding skilled performance behaviours in climbing.

4.2 Methods

The articles selected for review were obtained via searches of MEDLINE, SPORTDiscus and Embase databases up to January 2015. Keywords related to climbing (including: climbing, rock climbing, ice climbing, indoor climbing, bouldering, sport climbing, speed climbing) and skill (including: skill, performance, transfer, learning, adaptation, analysis, variability, behaviour, route finding) were searched in combination. Articles were included for review if they reported a spatial and/or temporal or activity type estimate (e.g. percentage of time spent in a specified activity state) of performance behaviors while climbing a graded route (Draper, Canalejo, et al., 2011). Articles where the goal of the task was not to get to the end of the route (but, for example the task consisted of participants adopting an instructed posture or reach and grasp action), were excluded (for example, Bourdin, Teasdale, & Nougier, 1998; Quaine, Martin, Leroux, Blanchi, & Allard, 1996; Testa, Martin, & Debu, 1999). The logic behind the exclusion criteria was that previous studies having demonstrated that task goals have important impacts on skilled behaviour (Cañal-Bruland & Van der Kamp, 2009;

Travassos et al., 2013). Full articles were then obtained and the reference lists were searched by hand to identify other potential studies.

4.3 Results

Data from the chosen studies (a total of 21 indexed, peer reviewed journal articles involving 22 separate experiments) were summarised and stored to a table and included sample, study design, task characteristics, measurements and significant effects (the extracted information from the studies can be seen in the Supplementary Material for this chapter). Non-indexed papers have been included in the discussion where of interest for future research (nine conference papers, Dovgalecs et al., 2014; Grushko & Leonov, 2014; Ladha, Hammerla, Olivier, & Plötz, 2013; Orth, Davids, & Seifert, 2014; Pansiot, King, McIlwraith, Lo, & Yang, 2008; Robert, Rouard, & Seifert, 2013; Schmid, Shea, Friedman, & Srivastava, 2007; Seifert, Dovgalecs, et al., 2014; Seifert, Orth, Herault, & Davids, 2013).

4.4 Discussion

4.4.1 Skilled behaviour and climbing

Quantifying spatial and temporal fluidity in climbing is important because it reflects an approach to measuring a general construct of skilled behaviour. Following Newell (1996), the performance of a skilled individual reflects a refined organization of behaviour, where efficiency is a significant constraint (i.e. the ratio of mechanical work to energy expenditure). Optimization in efficiency reflects that passive, mechanical and inertial properties of the limbs and body are fully exploited during performance. Optimized behaviour is characterized by smoothness and fluency (Newell, 1996). Smoothness refers to the organization of actions around a minimization of jerk (the third derivative of displacement, (Hreljac & Martin, 1993)). Fluency refers to the linking of movements in the spatial or temporal domains. Fluency is interrelated with smoothness in that the amount of curvature in an action has a relationship to the number of sub-movements required (Elliott et al., 2010), such that the degree of curvature tends to increase the number of sub-movements that are used (Arshi, Nabavi, Mehdizadeh, & Davids, 2014; Milner, 1992). Hence, the greater the curvature of a movement, the greater the potential increase in the jerk dimension. Indeed, the definition of skilled climbing follows the general definition of skilled behaviour provided above. Cordier et el. (1996), for example, referred to the behaviours of expert climbers as ‘fully adapted’. According to Cordier et el. (1996) expert route finding is optimally organized toward behavioural states that are compatible with the environment at the lowest energy cost. Optimized energy cost in climbing referring to the organization of behaviour toward a dissipative minimum of forces (Cordier et al., 1996, p. 804). Similarly, optimal route finding in climbing has been measured using spatial and temporal estimates of fluency and smoothness calculations, seeming to fit well theoretical frameworks related to skilled behaviour.

For example Bernstein (1967) considered that how individuals manage the biomechanical degrees of freedom during performance reflects their experience. Beginners, appear to restrict (or freeze up) the number of degrees of freedom involved during performance (Vereijken, van Emmerik, Whiting, & Newell, 1992). In climbing, freezing of the degrees of freedom would correspond to becoming immobile or using smaller, more rigid, slower, and less efficient movement patterns (Cordier, Mendès-France, Bolon, et al., 1994; Llewellyn, Sanchez, Asghar, & Jones, 2008; Nieuwenhuys et al., 2008; Pijpers et al., 2006). In contrast, experts appear to open up their available degrees of freedom to a much greater extent to the influence of the constraints in the environment (Button, Macleod, Sanders, & Coleman, 2003). In climbing, experts can adapt a broader range of behaviours. These might take the form of variations of grasping or foot positioning actions that can be used and which are functional for smooth, fluid traversal (for an list of climbing specific technical actions see, Phillips, Sassaman, & Smoliga, 2012). Indeed, skilled climbers are said to produce a series of well-formed and linked together movements, that give a structure to their adaptive capacity with respect to the environment (Cordier et al., 1993, p. 371; Cordier, Mendès-France, Bolon, et al., 1994). Draper et al.

(2011) also commenting that route selection and a climber's movement repertoire can enhance climbing economy (p. 459).

4.4.2 Spatial and temporal measures of skilled adaptation to route properties in climbing

Approaches to observing skilled climbing behaviour has included the coordination of actions to route properties during climbing, providing insights on the quality of movement adaptations undertaken. A number of studies have incorporated spatial and temporal measures into a single outcome to quantify climbing fluency (Seifert, Orth, et al., 2014). Such performance measures have resulted in analyses of velocity (Cordier et al., 1996; Sibella et al., 2007), acceleration (Cordier et al., 1996; Sibella et al., 2007) and jerk (Ladha et al., 2013; Pansiot et al., 2008; Seifert, Orth, et al., 2014).

For example, Seifert et al. (2014) calculated jerk coefficients on 3D hip translation and rotation accelerations separately. This approach provided a measure of smoothness of the hip during climbing ascent which was sensitive to both route design properties and practice. Specifically, jerk coefficients improved with practice on a route that involved the use of different types of grasping actions (overhand grasping and pinch grips), compared to no significant change on a route that required only use of a single action (overhand grasping) (Seifert, Orth, et al., 2014). The approach reported by Sefert et al., (2014) was, however, limited in that the normalization to distance reflected a global estimate across all participants and was not calculated on a climb by climb basis. In the case of locally based trajectory coordinates taken with a global reference, jerk can be obtained by first estimate as a continuous time series the climbers centre of mass (COM) in the plane of interest such that:

Jerk = Sum of (Horizontal length^6 + Vertical length^6) x (Horizontal length^6)/Path length

Noting that in dividing by the path length dimensionless units are obtained such that:

Path length = (Horizontal length + Vertical length)^2

Equation 4-1. Jerk coefficient of translation.

Of additional concern is, that, expertise in climbing is likely to involve highly adaptive and proficient performance along spatial and temporal dimensions in combination. Thus, understanding of skill and practice effects can benefit by considering each dimension separately (Cordier et al., 1996; Sibella et al., 2007). In the following section different approaches to quantifying indicators of fluency specific to each dimension are evaluated.

4.4.2.1 Spatial indicators of climbing fluency

Spatial indicators relate to analyses of displacement on a surface. Existing approaches include computation of the geometric index of entropy (GIE) (Boschker & Bakker, 2002; Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994; Pijpers et al., 2003; Sanchez et al., 2010; Sibella et al., 2007), climb distance (Green, Draper, & Helton, 2014; Green & Helton, 2011; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013), hand movement distances (Nieuwenhuys et al., 2008), COM to wall distance (Russell, Zirker, & Blemker, 2012; Zampagni, Brigadoi, Schena, Tosi, & Ivanenko, 2011), inter-limb relative positioning (Seifert, Coeurjolly, et al., 2013; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, L'Hermette, & Herault, 2011; Seifert, Wattebled, et al., 2013), and planar displacement at the athlete's COM (Zampagni et al., 2011).

Interpreting the quality of displacement with respect to a route is unique to measurement of the GIE (Boschker & Bakker, 2002; Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994; Pijpers et al., 2003; Sanchez et al., 2010; Sibella et al., 2007). The additional variables noted above are limited in terms of assessing fluency because they are not designed to detect adaptation to route properties. Rather, quantifying the absolute amount of displacement of the hips and the distance of the COM perpendicular to the wall plane can differentiate the behaviour of individuals according to their prior experience (Russell et al., 2012; Seifert, Coeurjolly, et al., 2013; Seifert, Wattebled, et al., 2014; Seifert et al., 2011; Seifert, Wattebled, et al., 2013; Zampagni et al., 2011) or can provide indications of anxiety (Green et al., 2014; Nieuwenhuys et al., 2008) and how attention is allocated (Green et al., 2014; Green & Helton, 2011).

4.3.2.1.1 Geometric index of entropy

The GIE is calculated by recording the distance of the path covered by the hips (L) and the perimeter of the convex hull around that path (c).

Such that:

$$GIE = \log^2(2L/c)$$

Noting that the outcome is then divided by the natural logarithm ($\log^2$) to place GIE in dimensionless terms.

Equation 4-2. Geometric index of entropy.

According to Cordier et al., (1994) the GIE can assess the amount of fluency of a curve. The higher the entropy value, the higher the irregularity of the climbing trajectory. Whereas the lower the entropy value, the more regular is the route trajectory. GIE has a number of advantages in that it is based on theoretically generalizable principles (Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994), is readily interpreted with respect to climbing activity (Cordier et al., 1993), and is effective for detecting skill (Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994), learning (Cordier, Mendès-France, Pailhous, et al., 1994) route (Orth et al., 2014) and technique effects (Boschker & Bakker, 2002; Sibella et al., 2007). Furthermore, data collection to perform an entropy calculation is relatively straight forward involving use of a single camera. Therefore, GIE is readily obtained in ecological performance contexts (Sanchez et al., 2010). Refer to Figure 4.2 below for an example of how entropy is calculated.

Theoretically, GIE is interpreted with respect to concepts drawn from non-linear thermodynamics for observing a system's self-organisation tendencies (Cordier et al., 1993). This model suggests that a movement system can be characterised as minimising energy expenditure in the dissipation of forces by exploiting available degrees of freedom in movement pattern formation (Bruineberg, 2014; Kugler & Turvey, 1987). Through a process of managing energy, climbers exploit available degrees of freedom to dissipate energy to a manageable degree. Where, a useful indication of the relative level of stability of a complex adaptive system is the degree of entropy it exhibits (Bruineberg, 2014; Edelman & Gally, 2001). Low levels of entropy suggest behavioural certainty and stability (more straight forward and fluent performance behaviour) and higher levels of entropy indicate behavioural uncertainty and instability (more complex, chaotic and less fluent movement, (Cordier, Mendès-France, Pailhous, et al., 1994)).

The interpretation of entropy is, however, limited to spatial considerations along a single plane of analysis, and important anterior-posterior plane features of climbing movements (Robert et al., 2013; Russell et al., 2012; Zampagni et al., 2011) may be missed. Of additional concern, is that if a climber is blocked at certain points in the climb, GIE will not be influenced, unless, there an increase in the length of the climbing trajectory during this time. If no exploration is evident in terms of hip translation during a stoppage, GIE will not be affected (see also Figure 4.2). Furthermore, the measurement is not sensitive to rotation, which is a behaviour climbers can exhibit when undertaking specific movement patterns, such rolling motions at the hip (Seifert, Orth, et al., 2014). This concern has previously been alleviated by undertaking separate analyses at each plane of action on the COM measure taken with reference to multiple cameras (Sibella et al., 2007). However, this approach is problematic from a statistical perspective, increasing the rate of family-wise error.

4.4.2.2 Temporal indicators of fluency

Temporal measures interpreted with respect to continuity of climbing performance include the: (i) relationship between static and dynamic movements at the hips (Billat et al., 1995; Cordier, Mendès-France, Bolon, et al., 1994; Fryer et al., 2012; Nieuwenhuys et al., 2008; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013; White & Olsen, 2010); (ii) relationship between hold grasping and moving between holds (Nieuwenhuys et al., 2008; Pijpers et al., 2005; Pijpers et al., 2006; White & Olsen, 2010); (iii) plateau duration at the hips (Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013); (iv) within-route climb time (Draper, Dickson, et al., 2011; Sanchez et al., 2010; Seifert, Wattebled, et al., 2013); (v) time spent in three-hold support (Sibella et al., 2007) and; (vi) movement frequency (Cordier et al., 1996). Additional measures such as response times (Pijpers et al., 2006) and absolute climb times have also been reported but do not pertain to the continuity of climbing. Rather, they have provided useful information on dual task effects (Green et al., 2014; Green & Helton, 2011; Pijpers et al., 2006) and can also be used for normalizing data (Billat et al., 1995).

A number of measures related to temporal fluency commonly place the amount of time spent in a climbing specific activity state with respect to another. Generally this has involved comparing the amount of continuous movement relative to the amount of stationary movements of the trunk (Billat et al., 1995; Cordier, Mendès-France, Bolon, et al., 1994; Fryer et al., 2012; Nieuwenhuys et al., 2008; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013; White & Olsen, 2010) or limbs (Nieuwenhuys et al., 2008; Pijpers et al., 2005; Pijpers et al., 2006; Sibella et al., 2007; White & Olsen, 2010).

Of additional interest are approaches that measure time spent in different parts of a route to measure adaptation to route specific properties. These measures are specific to climbing tasks embedded within a route and help to contextualize a specific experimental design. Such straightforward measures have been fruitful in detecting performance differences (whether or not individuals are more likely to fall (Draper, Dickson, et al., 2011)) and changes in within-route difficulty (such as in relationship to crux points (Sanchez et al., 2010)).

4.3.2.2.1 Immobility to mobility ratio

Data on the immobility to mobility ratio (IMR) are calculated by determining how long with respect to the total climb time an individual's COM or limb is spent in a stationary state relative to a moving state.

Such that:

IMR = time spent immobile/(time spent immobile + time spent mobile)

And is usually given as percentage time spent immobile or as a ratio value between time spent immobile to time spent mobile.

Equation 4-3. Immobility ratio.

Hence the higher the IMR, the longer the individuals COM or limbs are considered not moving. According to Billat et al. (1995) the time spent immobile reflects time under isometric contraction. Depending on the nature of the hand holds this period will either increase fatigue in the finger muscles (a key constraint for maintaining contact with a climbing surface (Vigouroux & Quaine, 2006)) or provide an opportunity to allow these muscles to recover (Fryer et al., 2012), an interpretation extended to analyses of the hips and hands (White & Olsen, 2010). Hence, the IMR has been used to reflect strategic behaviours with respect to the demands on the physiological system imposed by route design (Billat et al., 1995; Fryer et al., 2012; White & Olsen, 2010). It has also shown sensitivity to skill effects (Fryer et al., 2012), where experienced climbers can modify their IMR relative to their intrinsic physiological state, whereas inexperienced climbers do not appear to use periods of immobility to regulate their internal states, such as to manage heart rate (Fryer et al., 2012). White and Olson (2010) also speculated that a high IMR at the hip, in the case of bouldering, reflects an inability to perceive how to move through a route continuously, reducing performance in the activity. Sanchez et al. (2012) provides some evidence related to this, showing that more experienced climbers spent longer at rest locations within routes, when not given an opportunity to view the route from the ground. This suggested that immobility within the route can be used to visually inspect upcoming holds. Similar arguments have also been put forward for the behaviours of beginners, where increased IMR has been linked to a reduced capacity to effectively perceive climbing opportunities during traversal (Pijpers et al., 2005; Pijpers et al., 2006), a factor moderated by both anxiety (Pijpers et al., 2005; Pijpers et al., 2006) and fatigue (Pijpers, Oudejans, & Bakker, 2007).

A disadvantage of IMR is that the criteria for classifying an individual as immobile can be open to subjective interpretation. For example, criteria for dynamic climbing have included statements like: ‘progress of the hips was observed' (Billat et al., 1995) whereas, criteria for static climbing have included: ‘no discernible movement in pelvic girdle' (White & Olsen, 2010), and, ‘any point throughout the climb where the hips were not in motion' (Fryer et al., 2012). In addition to these approaches, a definition based on a movement threshold has also been used in an ice-climbing task. That is, immobility was considered when, along the vertical axis, pelvis displacement less than the value of 0.15 m for durations longer than 30 s (Seifert, Wattebled, et al., 2014). This approach however was also limited, requiring manual digitisation of the hips and was limited to analysis of vertical displacement behaviours. Furthermore, in indoor or rock climbing contexts, the thresholds applied in Seifert et al. (2014) are not recommended since ice climbing involves the additional concern of securing hooks. Since immobility is generally determined as the lack of displacement overtime, directly using the velocity is a recommended solution. For example, through an optimisation procedure appropriate thresholds can be determined, and which should be done for each climbing specific context. For an example, Figure 4.1 shows a threshold tested from 1 cm/s to 100 cm/s on a frontal plane time series trajectory in an intermediate individual climbing a level 5b (French rating scale of difficulty) route under top-roped, indoor conditions. In this case, the inflection point was shown to be about 27 cm/s. Future research should be directed toward determining whether specific thresholds are needed across different climbing domains and tasks constraints.

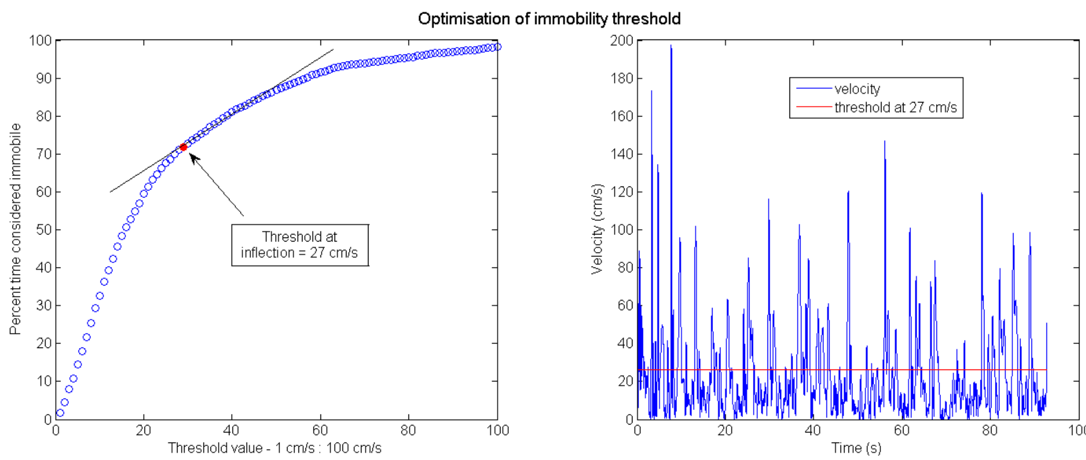

Figure 4-1. Optimisation procedure to determine a velocity based immobility threshold in indoor top-rope climbing. **cm/s** = centremetres per second, **s** = seconds.

Similar problems of objectivity underpin current approaches for determining limb IMR calculations that, when based on video analysis, need an operator to determine whether a limb is moving between holds (mobile) or is in contact with a support surface (immobile) (Pijpers et al., 2006; White & Olsen, 2010). Immobility at the limbs is also interpreted as time spent in isometric contraction, but this interpretation is limited in the absence of spatial data related to a limb's absolute and relative positions. For example, different gripping techniques provide the possibility to vary the limb angle, which might afford more or less rest while grasping a hold and immobile (Amca, Vigouroux, Aritan, & Berton, 2012). This is also true in terms of the postures that climbers can adopt. For example, when sitting away from the wall with arms extended, passive forces can be exploited for remaining on the wall at a reduced energy cost (Russell et al., 2012; Zampagni et al., 2011).

Of additional concern is that the immobility ratio removes from consideration (ir)regularity in the temporal dynamics of climbing behaviour. Cordier et al. (1996) for example undertook a spectral dimension analysis of the last five practice trials (out of ten) showing that temporal movement dynamics of experts were periodic, generating a vertical displacement at the hips at regular intervals of 3 seconds. In fact, it is possible that a climber could remain immobile at single location on the wall, with the remaining climb time measured as mobile. More effective approaches for understanding immobility dynamics and potential relationships between mobility and climbing fluency are needed. These various concerns are summarised using exemplary data in Figure 4.2 below.

Specifically Figure 4.2 shows how GIE is calculated with respect to the path and convex hull. The convex hull used in the entropy calculation in Fugure 4.2 is shown as black dashed lines. The white line is the detected hip position. Red parts of the line indicate immobility and blue parts of the line indicate mobility. The marker size linearly increases as a function of time spent in a given state. Hence, the larger the marker, the longer the individual has spent in the detected state (note that immobility was determined when this individual moving less than 27 cm/s). In this example, different relationships between immobility and entropy are shown as a function of wall position. Whilst highest entropy was shown at the middle part of the route, the highest immobility was shown at the highest part of the route.

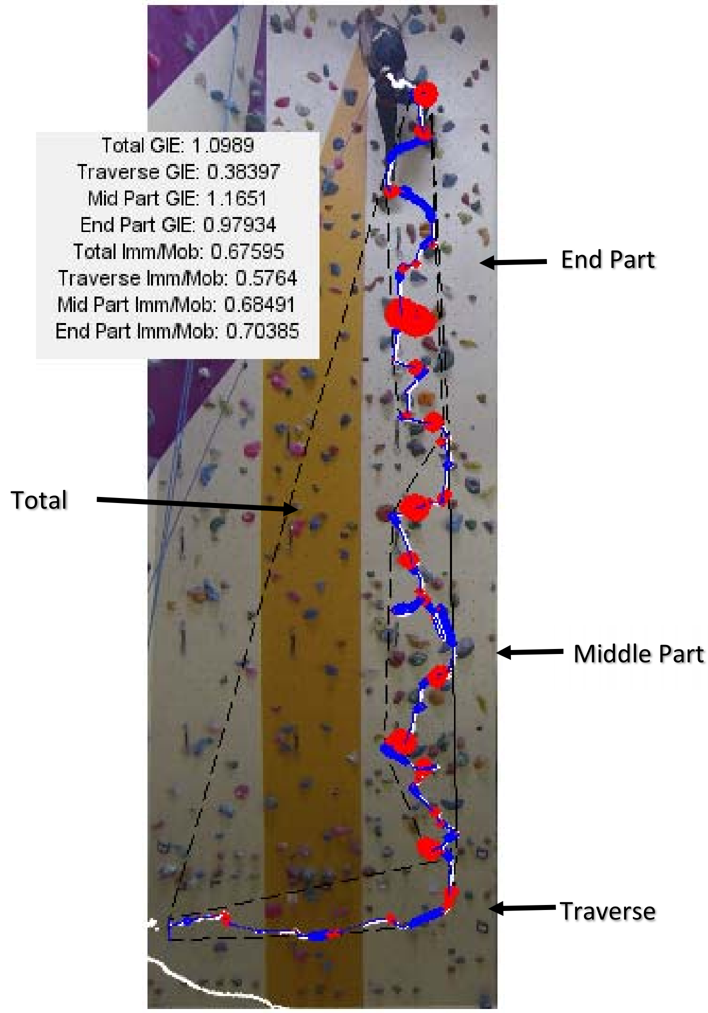

Figure 4-2. The relationship between entropy and immobility as a function of wall position. **Imm/Mob** = immobility to mobility. **GIE** = geometric index of entropy. **Mid** = middle.

Finally and of major concern in understanding the functionality of immobility, is that studies that have included an analysis that estimate the climber's intentions during periods of immobility, have revealed behaviours with a performatory or exploratory quality (Pijpers et al., 2005; Pijpers et al., 2006). An action is defined as performatory if it is undertaken to achieve a certain goal, and, exploratory if the behaviour is intended to gather information or reduce uncertainty (Pijpers et al., 2006). During immobility, individuals can exhibit intentional behaviour with varying degrees of functionality that are dependent on individual skill level (Fryer et al., 2012; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013). For example, individuals might benefit from periods of immobility at the hips and longer periods of reaching because exploratory behaviour might be functional to determine more effective pathways through the route (Nieuwenhuys et al., 2008; Sanchez et al., 2010).

4.4.3 General limitations of measures of fluency

General limitations that are shared across the variables discussed have emerged and pertain to measurement and interpretation. Specifically, these limitations concern: the manual nature of video analysis, potential for assessment spatial and temporal data in isolation leading to different conclusions and finally, that activity analysis can moderate how measures of fluency are interpreted.

4.4.3.1 Limitations in measurement

In the extant literature, the most common approach for data collection has been video filming of performance. The advantage of digital video is the possibility to collect real time data on movement behaviours across the various performance contexts relevant to climbing, including during competition (Sanchez et al., 2010; White & Olsen, 2010), and in indoor (Pijpers et al., 2003) and extreme outdoor environments (Seifert, Wattebled, et al., 2013). Video data are also straightforward to analyse involving a frame-by-frame analysis that can be confirmed using measures of within- and between-operator reliability (Seifert, Wattebled, et al., 2014). A major limitation in video-based approaches however, has been that they involve manual techniques to collect relevant data. Automatic methods using image-processing techniques are an option to overcome this methodological weakness and have been previously discussed (Orth et al., 2014). In addition to this concern is that most studies do not report correction techniques, most importantly in 2D image analysis being the correction of radial distortion and parallax (such as detailed in (Bradski & Kaehler, 2008)). Of additional concern is that, if appropriate, addressed should be any missing time series data that is capable of maintaining the spatial-temporal variance of the recorded behaviour. In this case techniques such as interpolation are not recommended. Finally, smoothing techniques are necessary primarily due to pixel based abstractions and should also be reported (such as detailed in (Hamill &

Knutzen, 2006)). Examples of how to address these various concerns are summarised in Figure 4.3 below.

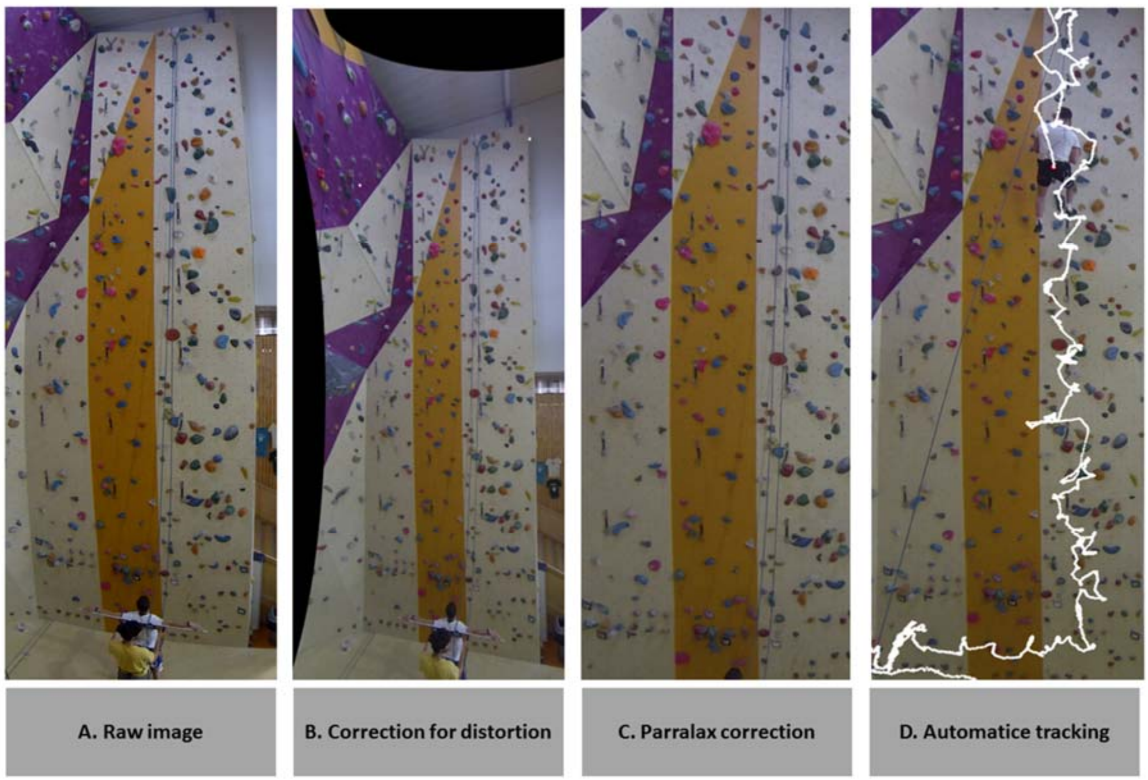

Figure 4-3. Recommended correction methods in planar video-based analysis of climber trajectories.

Specifically, Panel A shows a still image of video footage taken behind the climber at midway height and appropriate distance to observe the entire plane of interest. The plane of interest (climbing wall) is clearly distorted by fish eye and parallax. Panel B show distortion when corrected. Panel C shows the outcomes of parallax correction. Panel D shows the outcomes of an automatic tracking procedure, in this case a red light attached to the climbers harness was tracked using a classical Kalman filter. Once this position is obtained the lens distortion and parallax correction is then applied.

Finally, currently, acquiring time series data related to what each limb is doing (reaching, grasping, exploring etc.) is limited to manual annotation. Promising for future research is the emergence of worn sensor technology (Ladha et al., 2013; Pansiot et al., 2008; Schmid et al., 2007; Seifert, L'Hermette, et al., 2014) (for a review see Chambers, Gabbett, Cole, & Beard, 2015), capable of collecting the necessary data to automatically determine behavioural states such as reaching and grasping or dynamic and static coordination states at the hips (Dovgalecs et al., 2014; Seifert, L'Hermette, et al., 2014).

4.4.3.2 Relationships between spatial and temporal measures of fluency

Whilst spatial and temporal measures provide important information in isolation, interpreting the nature of movement adaptions during climbing can be enhanced by considering their outcomes in combination. For example, Sibella and colleagues (2007) interpreted a combination of low entropy at the COM and low absolute velocity as an agility style of climbing, characterizing a climber who tended to move slowly and cautiously through the route. This was contrasted with a power style of climbing that was associated with high entropy at the COM and large absolute velocity. Both climbers had the same reported ability level and were climbing under self-preferred conditions. Hence, the outcome variables in combination revealed preferences in climbing style that were based on the individuals' personal characteristics. Specifically, agility climbing was preferred by the lighter, less muscular individual and power style climbing appeared to be preferred by the stronger individual (Sibella et al., 2007).

4.4.3.3 Understanding measures of performance fluency can be improved by considering the intentionality of climbers

The major limitation in understanding the results of investigations of performance fluency is that they provide no functional explanation underpinning fluency outcomes (Seifert, Orth, et al., 2014). This is of major concern because, without an understanding of the functional behaviours that occur during periods of immobility or increased entropy, these data may be mistakenly concluded as dysfunctional. The study by Fryer and colleagues (2012) illustrates this point, showing that more experienced climbers exhibited a greater percentage of time immobile compared to less experienced individuals. An activity analysis was also carried out into the types of behaviours undertaken during rest. The results showed that the more experienced climbers spent more time during periods of immobility actively resting, either applying chalk to their hands or shaking their hands during time spent immobile. These findings highlight how interpreting intentions of climbers can provide insights on the functionality of measures that pertain to fluency. Without the additional measures from the activity analysis, it may have been erroneously concluded that the climbers were stopping more due to the greater physiological demand imposed by the route. In actual fact, it was the climbers' self-management of their internal states relative to their exploitation of opportunities for rest in a climbing route, a skill-dependent performance behaviour (Fryer et al., 2012).

4.4.4 The role of activity analysis in climbing for understanding fluency

It is generally assumed that the task goal corresponds to the intentions of the individual. In most climbing genres, the goal of the task is to climb to the end of a route using an efficient pathway, without prolonged pauses and without falling. However, intentions can interact with skill and dynamically change during performance as adaptations emerge to relative to dynamics constraints (Balagué, Hristovski, & Aragonés, 2012; Davids, Araújo, Seifert, & Orth, 2015; Guerin & Kunkle, 2004). Hence, estimates that pertain to the intentions of individuals during performance can help place performance outcomes in perspective with what an individual was trying to achieve.

Intentions of climbers relate to goals underpinning why they perceive and act in a certain way (Seifert, Wattebled, et al., 2014). Seifert et al., (2014) for example showed that expert ice-climbers reported their intentions to maintain energy and economy though focusing perception and action toward specific intentions, their perception of information related to the usability of holes and their actions toward the use of holes in the existing ice surface structure. On the other hand, Seifert et al.,

(2014) showed that the intentions of inexperienced climbers pertained to stability, where perceptions were focused on information related to the size of holes in the ice wall and their actions were motivated primarily for achieving deep, secure, anchorages during ascent. Inexperienced climbers displayed significantly longer periods of immobility at the hip, higher amounts of swinging actions, prior to making a definitive anchorage with their ice-tools, and tended to adopt a X-like body position. Whilst the inexperienced climbers showed poor performance in terms of fluency, their performatory and exploratory actions were in correspondence to their intention to avoid falling.

Ecological models of performance and learning, such as ecological dynamics (Davids et al., 2015), acknowledge that prior experience influences the intentions of individuals as they are adapted to a specific performance context (see also, Jacobs & Michaels, 2007; Warren, 2006). The intentions of the individual shape why they couple their actions to specific information sources, having a direct impact on perceptions and actions and vice versa (Jacobs & Michaels, 2007). If an individual has not adapted structural (Vigouroux & Quaine, 2006) and/or functional (Bläsing, Güldenpenning, Koester, & Schack, 2014) characteristics that support fluent climbing, it makes sense that the behaviors that an individual exhibits during periods of immobility or increased entropy can be functional to primarily avoid falling (Sanchez et al., 2010; Seifert, Wattebled, et al., 2014), or to explore ways to avoid falling in future attempts (Orth et al., 2014; Seifert, Orth, et al., 2013). In these respects, although less experienced climbers are generally associated with 'jerkier, more rigid, and slower movements' (Boschker & Bakker, 2002; Cordier, Mendès-France, Pailhous, et al., 1994; Seifert, Orth, et al., 2014; Sibella et al., 2007), activity analysis for gathering data on performatory and exploratory actions might reveal that a lack of fluency has functional relevance (Seifert, Wattebled, et al., 2014).

4.4.4.1 Performatory behaviours

According to Pijpers and colleagues (2006), performatory actions are meant to reach a certain goal. Specific performatory actions have included, moving a hand or foot from one hold to the next to use it as support for further climbing actions (Nieuwenhuys et al., 2008; Pijpers et al., 2006; White & Olsen, 2010); using a hold to move the entire body vertically or ascend the route (Sanchez et al., 2012; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013); using a hold to support recovery actions (Fryer et al., 2012; Sanchez et al., 2012); and making visual fixations in direct combination to a movement (Nieuwenhuys et al., 2008).

Theoretically, performatory actions correspond to behaviours that are intended for traversal. If performatory actions are effective they should improve fluency, by reducing the amount of time spent immobile and contribute to ongoing progression through the route. The value of collecting data on fluency indices, is that it is not the absolute number of performatory actions that can determine whether a climber is using holds efficiently. For example, a climber might skip holds, use a more difficult movement (Sibella et al., 2007) or use less advanced actions (Boschker & Bakker, 2002) which might result in more or less fluid climbing performance.

4.4.4.2 Exploratory behaviours

Exploratory actions, on the other hand, are primarily information gathering movements (Pijpers et al., 2006) where the type of information important in climbing can pertain to different modalities such as haptic, auditory, visual and kinesthetic (Seifert, Wattebled, et al., 2014; Smyth & Waller, 1998). Exploratory actions have included: when climbers explore whether a hold is within reach (Pijpers et al., 2006); when a hold is touched without being used as a support (Nieuwenhuys et al., 2008; Pijpers et al., 2006; Sanchez et al., 2012; Seifert, Orth, et al., 2014; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013); when an anchorage is weighted to test its fallibility (Seifert, Wattebled, et al., 2014); when tools are used to swing without a definite anchorage (Seifert, Wattebled, et al., 2014; Seifert et al., 2011; Seifert, Wattebled, et al., 2013); and when a fixation occurs when an individual is not moving to a new hold (Nieuwenhuys et al., 2008).

When exploratory indices of behaviour increase, this is generally associated with poorer performance on measures of fluency. For example, if a climber stops because he/she cannot perceive an effective path (a problem of route finding, Cordier et al., 1993; Sanchez et al., 2012), through the route this should be associated with a higher frequency of hold exploration (Pijpers et al., 2006) and increased GIE (Cordier, Mendès-France, Pailhous, et al., 1994). Furthermore, as exploration reduces, fluency may also improve in correspondence (Seifert, Orth, et al., 2014; Seifert, Orth, et al., 2013), suggesting a relationship between exploration, learning and performance.

Exploration indices are currently limited to haptic exploration at the hands and it is likely more experienced individuals show exploration across different levels of analysis and that may be more optimal. For example, pre-route visual inspection can assist a climber to locate regions to rest within a route (Sanchez et al., 2012), but, the ability to locate these regions during preview have been shown to be experience-dependent and that route difficulty also moderates visual exploration directly (Grushko & Leonov, 2014). Additionally, whereas, experienced climbers might focus on properties of hold usability (a functional property), and less experienced individuals might focus on hold graspability (a structural property) (Boschker, Bakker, & Michaels, 2002). Another example of this is that, haptic exploration may be specific to ascertaining hold reachability or graspability, being revealed in terms of touching but not grasping a hold or modifying the grip whilst in contact with a hold. Other forms of exploration, therefore, such as body orientation or configuration, might instead be specific to exploration of functional properties such us how to use a hold or pass between holds. It would be anticipated that these behaviors can be constrained by an individual's ability to perceive body- or action-scaled relationships (Dicks, Davids, & Button, 2010; Pezzulo, Barca, Bocconi, & Borghi, 2010; Ramenzoni, Davis, Riley, & Shockley, 2010). For example, a climber's visual exploration might be constrained by how far he/she is able to reach (a body-scaled constraint), or he/she may ignore holds that are too small to apply forces at (an action-scaled constraint).

4.4.5 General limitations in activity analyses

Performatory and exploratory behaviors are likely to be observable across many more indices. For example, behaviours might include the overall organization of the body (Seifert, Dovgalecs, et al., 2014) or different climbing gait patterns used for progressing through routes (Russell et al., 2012). Actions might also be evident across multiple levels, such as the visual-motor level (Nieuwenhuys et al., 2008) or at more refined levels of control such as the nature of hand grasping actions (Fuss & Niegl, 2008) (such as when modifying the hand grip whilst in contact with a hold). Additionally, both the upper and lower limbs clearly have important roles in climbing, and their relationships remain poorly understood and often analyzed separately (Seifert, Coeurjolly, et al., 2013) with potential limb dominance effects currently unexplored.

4.5 Conclusion

This chapter has evaluated the importance of relating fluency and activity type measures for understanding climbing behaviours. Future research that can successfully integrate these approaches can clearly provide better explanations for understanding performance and learning dynamics in climbing. A number of limitations have been raised throughout this review in regards to the types of measurements used to estimate fluency and activity types during climbing tasks, how fluency measures can be interrelated to other measures of fluency and those pertaining to performatory and exploratory behaviour.

Approaches outlined in this review significantly advance understanding of climbing skill. According to the perspective promoted in this review, performance in climbing is understood by the way a route is climbed. Fluency measures, capturing spatial and temporal performance dimensions when integrated with estimates of the climber’s exploratory and performatory behaviour can reveal insights into the adaptations of individuals to route properties, with activity analysis shown to assist in explaining the functionality of measures that pertain to fluency.

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Supplementary Material for Chapter 4

Supplementary Table S4-1. Included studies.

Study[a]	Sample[b]	Design[c]	Task[d]	Measure[e]	Outcome[f]
	Spatial & temporal measures of skill				
Sibella, Frosio, et al. (2007) [RM] [Journal article]	N = 12, 30.6 yrs16-49, recreational, non-competitive climbers, training 1-2 x per week: agility style climber subgroup (n = 1); force style climber subgroup (n = 1)	A. Skill [**note**: skill groups formed post-hoc, by identifying different climbing strategies using kinematic measures]	Climb (indoor, artificial, top-rope, F-RSD = 4b [0.25, Lower grade], 3 m traverse, 3 m ascent) self-preferred [**note**: t x 5, data averaged across participants]	Movement (COM) multi-camera: 1. GIE [**note**: computed for frontal, saggital and transverse planes] 2. absolute velocity (COM) 3. absolute acceleration (COM) 4. power of acceleration time course (COM) 5. mean number of holds in contact per recorded frame of video (60 hz)	1 was significantly lower (frontal and sagittal planes), 3 and 4 was significantly lower, and 5 was significantly higher in the agility style climber compared to the force style climber; 2 was significantly lower in the agility style climber compared to the entire group of climbers and 2 was significantly higher in the force style climber compared to the entire group of climbers.
	Spatial				
Boschker & Bakker (2002) [MMD] [Journal article]	N = 24,18-28 yrs, no experience: control subgroup (n = 8); dual grasping model subgroup (n = 7); arm-crossing technique model subgroup (n = 9)	A. Pedagogical intervention (model) i. control (observed the climbing wall) ii. simple technique model (observed an expert climber 4 times using a basic climbing technique)	Climb (indoor, artificial, top-roped, F-RSD = 5c [1, Intermediate], crux = 1, 7 m height, 3.5 m width, 98.2 deg relative to floor, 22 holds) instructed to climb using the same	Movement (hip trajectory, discrete actions) single camera: 1. GIE 2. falls [climb time]	At trial 2, 3 and 4, the advanced technique subgroup climbed significantly faster than the control and simple technique subgroup; at trial 1, 1 was significantly lower in the advanced technique

		iii. advanced technique model (observed an expert climber 4 times using an advanced climbing technique) B. Practice (t x 5) [**note**: all observations were on a video, when observing the expert model, playback speed was first in slow motion (x2) and then normal (x2)]	technique as observed model otherwise self-preferred		subgroup compared to the simple technique subgroup and significantly lower in the control subgroup compared to the simple technique subgroup; at trials 2, 3 and 4, 1 was significantly lower in the advanced technique subgroup compared to the control and simple technique subgroups
Cordier, Mendès-France, et al. (1993) [MMD] [Journal article]	N = 7: average skill subgroup (n = 3, F-RSD = 6b-6c [1.75-2.25, Intermediate]); highly skilled subgroup (n = 4, F-RSD = 7a-7b [2.5-3, Intermediate-, Advanced])	A. Skill B. Practice (t x 10)	Climb (indoor, artificial, top-roped, F-RSD = 6a [1.25, Intermediate], ~10 m high) self-preferred	Movement (hip trajectory) single camera: 1. GIE 2. fractal dimensions [climb time]	1 was significantly lower in highly skilled subgroup; 1 significantly decreased with practice in both groups; [**note**: a significant interaction effect between skill and practice showed that 1 reduced faster in the higher skilled subgroup compared to the lesser skilled subgroup; a clear correlation was shown between climb time and entropy with higher climb times being associated with higher entropy]
Cordier, Mendès-France, et al. (1994)	Average skill subgroup (F-RSD = 6b [1.75,	A. Skill B. Practice (t x 10)	See above, Cordier, Mendès-France, et	Movement (hip trajectory) single	Highly skilled subgroup showed less 1

[MMD] [Journal article]	Intermediate]); highly skilled subgroup (F-RSD = 7b [3, Advanced]) [**note**: the exact number of individuals making up each sub-group not reported]		al. (1993)	camera: 1. GIE [climb time]	compared to the average skilled subgroup; with practice 1 significantly reduced; highly skilled subgroup reduced entropy faster with practice than the skilled group; [**note**: highly skilled subgroup reduced entropy to asymptote by trial three whereas the average skill subgroup did not reach a clear asymptote after 10 trials of practice]
Cordier, Mendès-France, Pailhous, et al. (1994) [MMD] [Journal article]	N = 10: non-expert subgroup (n = 5, F-RSD = 6b [1.75, Intermediate]); expert subgroup (n = 5, F-RSD = 7b [3, Advanced])	A. Skill B. Practice (t x 10)	See above, Cordier, Mendès-France, et al. (1993)	Movement (hip trajectory) single camera: 1. GIE [climb time]	Highly skilled subgroups showed overall less entropy compared to the average skilled subgroup; With practice entropy significantly reduced; Highly skilled group reduced entropy faster with practice than the average skilled group; Highly skilled group reduced entropy to asymptote by trial three. Unskilled group did not appear to reach asymptote.
Pijpers, Oudejans, et al. (2003) [RM] [Journal	N = 17, 11 M, 19-26 yrs, little to no experience in	A. Route design (height) i. mean height of foot	Climb (indoor, artificial, top-rope,	Movement (hip trajectory) single	1 and climb time significantly increased

article] – Experiment 2	climbing	holds 0.3 m from the ground ii. foot holds 3.7 m from the ground	flush vertical, 6 hand- and 5 foot-holds, 7 m height, 3.5 m width) **nr** [**note**: difficulty assumed as easily achievable; participants practiced on route before testing; each trial required 20 sec continuous climbing]	camera: 1. GIE [climb time, HR and state anxiety]	when climbing in the high condition.
Sanchez, Boschker, et al. (2010) [IG] [Journal article]	N = 19, 24.6 yrs±4.0SD, elite climbers, F-RSD = 7b+ to 8b [3.25-4.5, Advanced-Elite]: successful subgroup (n = 9); unsuccessful subgroup (n = 7) [**note**: successful subgroup membership criteria required that the climbers get to at least the 39th hold (out of 50). Those who did not were assigned to the unsuccessful subgroup.]	A. Skill	Climb (artificial, F-RSD = 7c+ [3.75, Advanced]], crux = 2, rest points = 2, on-sight, 16 m high, 50 handholds) competition [preview = 5 mins]	Movement (hip trajectory) single camera: 1. GIE (section 1 crux, section 1, section 2) 2. climb time (section 1 crux, section 1, section 2) [precompetitive state anxiety] [**note**: 16/19 of the climbers were analyzed; for analysis the route was broken into 2 sections and 2 crux points]	2 was significantly longer in the successful subgroup compared to the unsuccessful subgroup in the first crux.
Zampagni, Brigadoi, et al. (2011) [IG] [Journal article]	N = 18 M: elite subgroup (n = 9, 32.1 yrs±7.6SD, F-RSD = 7b-8b [3-4.5, Advanced-Elite], climbing age = 13.9 yrs); no experience subgroup (n = 9, 31.9	A. Skill	Climbing (artificial, top-rope, 20 holds, uniform holds = 13 cm high, 16 cm wide, 12 cm deep) under instruction [**note**: instructed on	Movement, applied force (COM, hands and feet) mulit-camera, instrumented holds: 1. COM anterior/posterior and lateral motion (min,	The expert subgroup climbed with 1 significantly further from the wall and with larger lateral displacements compared to the no

	yrs±8.5SD)		the sequence of which limb to reposition and to which hold, this pattern was repeated until climbers reached the top; climbers were required to complete each cycle within 4 seconds]	mean, max) 2. force (vertical component)	experience subgroup; 2 showed significantly larger oscillations in the expert subgroup compared to the no experience subgroup.
	Temporal				
Billat, Palleja, et al. (1995) [RM] [journal article]	N = 4, 22.2 yrs±2.3SD, F-RSD = 7b [3, Advanced], climbing age = 3 yrs	A. Hold (size) & Wall (slope) i. smaller more complex hold design ii. steeper slope [**note**: difficulty matched]	Climb (indoor, artificial, F-RSD = 7b [3, Advanced], red-point, 15 m high, ~10 deg overhang) self-preferred [**note**: 5 hrs practice on each route prior to testing]	Movement (discrete actions) single camera: 1. Dynamic time (discernable motion at the hips) 2. Static time (no discernable motion at the hips) [**note**: additional variables of interest related to oxygen consumption]	1 was significantly longer on the smaller more complex route compared to the route with a larger overhang.
Cordier, Mendès-France, et al. (1996) [MMD] [Journal article]	N = 10: non-expert subgroup (n = 5, F-RSD = <7a [<2.5, Intermediate]); expert subgroup (n = 5, F-RSD > 7a [>2.5, Advanced])	A. Skill B. Practice (t x 10)	See above, Cordier, Mendès-France, et al. (1993)	Movement (hip trajectory) single camera: 1. Frequency of movement (Hz) 2. Harmonic analysis	Expert subgroup generated approximately one movement every three seconds and were closer to the harmonic model by a factor of about two compared to the non-expert subgroup.
Draper, Dickson, et al.	N = 18, 12 M, 25.6±4.5	A. Route Type	Climb (indoor,	Movement (climb time)	Experience was the best

(2011) [MMD] [Journal article]	intermediate level, onsight lead F-RSD = 5+ [1, Intermediate], red-point F-RSD = 6a [1.25, Intermediate] climbing age 3.6yrs±3.1	i. tope-rope ii. lead rope B. Route completion i. yes (n = 11) ii. no (n = 7) [**note**: group formed post hoc based on those who did or did not fall]	artificial, F-RSD = 6a, 12.5 m height, 7 quick-draws) self-preferred	single-camera [yrs experience, NASA-TLX, CSAI-2D, oxygen consumption, blood lactate, HR] 1. Climb time (between successive quick-draws)	predictor of climbing success and was also correlated with confidence and faster climbing within challenging parts of an ascent. Climbers that fell were slower through the route
White & Olsen (2010) [Journal article] [RM]	N = 6, elite, age = 28yrs±5SD, climbing age = 16yrs±5SD [**note:** sample argued elite, held an IFSC World ranking for the World Cup boulder series and members of British national team]	Observational	Climb (indoor, artificial, bouldering) competition [a total of 12 climbs were recorded, two climbs per individual, each on a different route]	Movement (discrete actions) two-cameras: 1. hand contact time 2. reach time 3. dynamic time 4. static time [number of attempts, climb time, total attempt time, between attempt recovery time]	A larger proportion of time is spent in dynamic movement relative to static. Hand contact time was larger than reach time.
	Activity analysis				
Nieuwenhuys, Pijpers, et al. (2008) [RM] [Journal article]	N = 12, 7 M, 24.4 yrs±1.98SD, no experience	A. Route design (height) i. holds 0.44 m from the ground ii. holds 4.25 m from the ground	Climb (indoor, artificial, top-rope, 26 hand- and foot-holds) self-preferred [**note**: difficulty level assumed to be easily achievable; participants practiced on the route prior to testing]	Visual behaviour, movement (gaze-location, discrete actions) eye-tracker, single camera; 1. fixation (duration, number, average duration, duration per location, duration per type, search rate) [**note**: possible fixation locations included handholds, hands, wall, other and possible fixation types were exploratory or	Climb time, movement time between holds and time spent static was significantly longer and number of movements were significantly greater in the high condition compared to the low condition; Fixation durations were significantly longer, number of fixations significantly increased, and search rate significantly decreased in the high condition

				performatory] 2. mean distance of fixation 3. movement time (climb time, stationary time, moving time (hands and feet), average movement duration between holds) 4. mean distance of hand movements [**nb**: additional measures of interest were HR and anxiety]	compared to the low condition.
Pijpers, Oudejans, et al. (2005) [RM] [Journal article] – Experiment 1	N = 8 M, 31.4 yrs±4.81SD, no experience	A. Route design (height) i. mean height of foot holds 0.4 m from the ground ii. foot holds 5.0 m from the ground	Climb (indoor, artificial, top-rope, flush vertical, flash, 7 m height, 3.5 m width, 7 hand- and 6 foot-holds, mean inter-hold distance = 0.15 m) as fast and as safely as possible without falling: [**note**: difficulty not given but assumed to be easily achievable; participants practiced on low traverse prior to testing and observed an expert model perform the traverse on video; each trial required 2 traversals]	Movement (discrete actions) multi-camera: 1. number of exploratory movements (number of times a hold is touched without use as support) 2. number of performatory movements 3. Use of additional holds (two holds not needed to achieve traversal were set into the route) [climb time, HR and anxiety data]	1 and climb time was significantly higher in the high condition compared to the low condition.

Pijpers, Oudejans, et al. (2006) [RM] [Journal article] – Experiment 2	N = 12, 6 F, 20.8 yrs±3.57SD, no experience	A. Route design (height) i. holds on average 0.36 m from the ground (t x 4) ii. holds 3.69 m from the ground (t x 4)	Climb (indoor, artificial, top-rope, flush vertical, 7 m height, 3.5 m width, 15 hand- and 15 foot-holds) as fast and as safely as possible without falling [**note**: difficulty not rated but assumed to be easily achievable; participants practiced on route before testing; each trial required 2 traversals]	Movement (discrete actions) single camera: 1. number of performatory actions (hands and feet) 2. number of exploratory actions (hands and feet) [climb time, state anxiety]	1, 2 and climb time increased significantly when climbing at height compared to close to the ground.
	Crossed				
Fryer, Dickson, et al. (2012) [IG] [Journal article]	N = 22: intermediate subgroup (n = 11, 7 M, F-RSD = 6a/ Ewbank = 18/19 [1.25, Intermediate], climbing age = 3±1.15yrs); advanced subgroup (n = 11, 10 M, F-RSD = 6c+/ Ewbank = 21/22 [2.25, Advanced], climbing age = 3.3±1.06yrs)	A. Skill	Climb (indoor, artificial, top-roped, F-RSD = 6a [1.25, Intermediate] & 6c+ [2.25, Intermediate], on-sight, 12.15 m high, overhang) self-preferred [preview = 5 min] [**note**: difficulty matched to subgroup skill levels]	Movement (discrete actions) single camera: 1. time spent static (no hip motion) 2. time spent actively resting (shaking the limbs) [**note**: additional variables of interest related to HR, mood state, anxiety]	Advanced subgroup spent significantly greater proportion of their climb time in static states and more of the static time actively resting compared to the intermediate subgroup; [**note**: significantly lower heart rates in the advanced subgroup compared to the intermediate subgroup are interpreted as related to the time spent in active recovery]
Pijpers, Oudejans, et al.	N = 15, 13 M,	A. Route design (height)	Climb (indoor,	Movement (discrete	1 and 2 (feet only) was

(2005) [RM] [Journal article] – Experiment 2	20.7±2.22SD yrs, no experience	i. mean height of foot holds 0.4 m from the ground ii. foot holds 4.9 m from the ground	artificial, top-rope, flush vertical, 7 m height, 3.5 m width, 6 hand- and 5 foot-holds) as fast and as safely as possible without falling: [**note**: difficulty not given but assumed to be easily achievable; participants practiced on low traverse prior to testing and observed an expert model perform the traverse on video; each trial; 4 traversals required per condition]	actions) mulit-camera, instrumented holds: 1. number of explorative movements 2. number of performatory movements (hands and feet) 3. rest between traversals 4. contact time (total, hands, feet, average per hold, total and for feet and hands) [climb time, HR, anxiety]	significantly greater and 4 (total, feet and hands, average total and average feet) was significantly longer in the high condition compared to the low condition. [**note**: climb time was significantly longer in the high condition compared to the low condition]
Sanchez, Lambert, et al. (2012) [MMD] [Journal article]	N = 29: intermediate subgroup, (n = 9, F-RSD = 6a – 6b [1.25-1.75, Intermediate]); advanced subgroup, (n = 9, F-RSD = 7a-7a+ [2.5-2.75, Intermediate-Advanced]), expert subgroup, (n = 11, F-RSD > 7b+ [>3.25, Advanced])	A. Skill B. Preview: i. with preview (3 min) ii. without preview	Climb (indoor, top-rope, on-sight) self-preferred [preview = 3 minutes (when given)] [**note**: a total of 6 routes were involved, route difficulties as follows: i. 2 intermediate routes (6a [1.25, Intermediate], 6a+[1.5, Intermediate]) ii. 2 advanced routes (both 6c [2.25, Intermediate]) iii. 2 expert routes	Movement (discrete actions) single camera: 1. number of movements (performatory & exploratory) 2. duration of movements (performatory & exploratory) 3. number of stops (appropriate & inappropriate) 4. duration of stops (appropriate & inappropriate)	3 (appropriate) and 4 (appropriate) were significantly longer when climbing without preview in the expert subgroups compared to the intermediate and advanced subgroups on the route matched to skill level.

			(7b, 7c [3.5, Advanced]); participants only climbed routes that were either equal to or less than their F-RSD level]		
Seifert, Coeurjolly, et al. (2013) [IG] [Journal article]	N = 15 M: expert subgroup (n = 7, 32.1 yrs±4.0SD, F-RSD = 7a+ to 7c [2.75-3.5, Advanced], F-RSD for ice falls = 6-7, rock-climbing age = 17.1, ice climbing age = 10.4 yrs); beginner subgroup (n = 8, 28.5 yrs±6.4SD, climbing age ~ 20 hrs practice on artificial walls, no experience in ice climbing)	A. Skill	Climb (outdoors, ice fall, 85 deg ramp, 30 m high, top-rope) self-preferred [**note**: Route difficulty: i. grade 5+ (F-RSD for ice-falls) i. grade 4 (F-RSD for ice-falls); participants only climbed routes that were equal to their F-RSD level]	Movement (upper and lower body) single camera: 1. exploration index (ratio of ice tool swings to definitive anchorages for upper and lower limbs) 2. relative angular position (upper and lower limbs pairs relative to the horizontal)	1 showed a 1:1 ratio in the expert subgroup for both the upper and lower limbs whereas 1 showed a ratio of 0.6 and 0.2 in the upper and lower limbs respectively in the beginner subgroup (i.e. more non performatory movements); 2 showed more variability in the relative angular positions in the expert subgroup compared to the novice subgroup.
Seifert, Orth, et al. (2014) [Journal article]	N = 8, 21.4yrs±2.4SD, top-rope, F-RSD = 6a [2, Intermediate], climbing age = 4.1yrs±2.1SD	A. Route design (holds) i. single edged (all edges parallel to ground) ii. double edged (one edge parallel to ground, one edge perpendicular to ground) B. Practice (4 trials)	Climb (indoors, artificial, top-roped, on-sight & practice, F-RSD = 5c [1, Intermediate] 10 m height, 20 holds, preview = 3 mins) self-preferred [**note:** each hold had two graspable edges]	Movement (hip) worn sensor 1. jerk coefficient (normalized) [**note**: rotation and position analysis] 2. Exploratory movements	1 was higher on double edged (more complex) route. 1 decreased with practice. 2 decreased with practice. [**note:** of additional interest was the strong correlation between rotational and positional coefficients of jerk]

Seifert, Wattebled, et al. (2013) [IG] [Journal article]	N = 15, 24.5 yrs±4.5SD, naïve ice climbers: novice subgroup (n = 10, F-RSD < 5 [<0.75, Lower grade], climbing age = 10 hrs practice on artificial walls); intermediate subgroup (n = 5, F-RSD = 6a [<1.25, Intermediate], climbing age = 3 yrs)	A. Skill [**note**: research question of interest was whether skill influenced transfer to different environmental properties based on the climbers history. IV corresponds to: B. Transfer i. rock climbing; ii. ice climbing.]	Climb (outdoors, ice, 30 m high, top-rope, route F-RSD for ice falls = 4) self-preferred	Movement (discrete actions) single camera: 1. exploration index (ratio of ice tool swings to definitive anchorages for upper and lower limbs) 2. relative angular position (upper and lower limbs pairs relative to the horizontal) 3. relative phase (upper and lower limb pairs) [**note**: see note in Seifert, Wattebled, et al., (2011)] 4. vertical distance climbed in 5 mins 5. plateau duration (plateau defined as less than 0.15 m of vertical displacement for longer than 5 s)	1 was closer to a ratio of one swing to one definitive anchorage for intermediate subgroup compared to the novice subgroup; 2 and 3 showed significantly greater variability in the intermediate subgroup compared to the novice subgroup; 4 was significantly greater and 5 was significantly shorter in the intermediate subgroup compared to the novice subgroup. [**note**: of additional interest in this study was to undertake an unsupervised hierarchical cluster analysis using the DVs to classify the climbers into different skill based subgroups.
Seifert, Wattebled, et al. (2014) [IG] [Journal article]	N = 14; expert climber subgroup (n = 7, 32.1±6.1SD, F-RSD for rock = 7a+-7c [2.75-3.5, Intermediate], F-RSD for icefalls = 6-7, climbing age = 17.4yrs±5.6); beginner subgroup (n = 7, 29.4 yrs±6.8, climbing age = <20hrs indoor	A. Skill	Climb (outdoors, ice, top-rope; 30 m high) self-preferred [**note**: a total of 2 routes were involved, the expert subgroup were tested on a grade 5+ (F-RSD for ice-falls); the beginner	Movement, verbalization (discrete actions, self-confrontation interview) single camera, audio: 1. number & duration of stops 2. relative angular position (upper and	Expert subgroup achieved greater vertical displacement, had more stoppages but that were shorter in duration, explored a larger angular range with ice-tools, less exploratory actions compared to beginner

	climbing practice)		subgroup were tested on a grade 4 (F-RSD for ice-falls)]	lower limbs pairs relative to the horizontal) 3. exploratory & performatory actions 4. Verbalisations i. perceptions ii. actions iii. intentions	subgroup. Expert subgroup verbalized about information related to behavioral opportunities that were multi-modal and intentions were focused on vertical traversal. Beginners focused on visual cues for putting their ice-hooks into the wall and focused intentions on remaining on the wall.

a, author (date) [experimental design] publication type [study number]
b, sample size; (sample characteristics: age, variability, climbing age, reported ability level [ability level converted to Watts, see Draper N, Canalejo JC, Fryer S, Dickson T, Winter D, Ellis G, Hamlinb M, Shearmanc J, North C. Reporting climbing grades and grouping categories for rock climbing. *Isokin Exerc Sci*. 2011: 19: 273-280.]); subgroups.
c, Independent variable: A, B; level: i, …, iii.
d, Task: climb; (route properties: location (indoors; outdoors), wall properties (artificial; rock; ice, height, slope), type (top-rope; lead), route difficulty [Watts conversion (see [b])] ; instructions; [preview time]
e, Dependent variable type; (level or nature of analysis); measurement device; dependent variable 1, …, 5 (description and sub-levels) [additional variables]
f, variable(s) reported showing significant effect: 1, … , 5 (description of direction of effect and reported interpretation as position or negative for performance)
Note that omitted information reflects unreported data.

baleyer = individual responsible for securing the ascent of the climber by operating the safety rope; **COF** = coefficient of friction; **COP** = centre of pressure; **CPEI** = climbing performance evaluation inventory; **CRP** = continuous relative phase; **Crux** = a part of a route more difficult than others; **deg** = degrees; **DV** = dependent variable; **F** = female; **flash** = individuals have had a chance to observe another climber on the route prior to making an attempt; **F-RSD** = french rating scale of difficulty; **IG** = Independent groups; **IV** = independent variable; **GIE** = geometric index of entropy; **HR** = heart rate; **hrs** = hours; **Hz** = cycles per second; **M** = male; **m** = metres; **max** = maximum; **min** = minimum; **mins** = minutes; **MMD** = mixed methods design; **NASA-TLX** = National Aeronautics and Space Administration Task Load Index; **nr** = not reported; **on-sight** = the first attempt of a climbing route; **PCA** = Principle component analysis; **red point** = refers to performance on a route that has been previously practiced; **s** = seconds; **SD** = standard deviation; **t** = trials; **UIAA** = Union Internationale des Associations d'Alpinisme; **vs.** = versus; **yrs** = years.

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CHAPTER 5. RESULTS PAPER 1

Constraints representing a meta-stable regime facilitate exploration during practice and transfer of skill in a complex multi-articular task

Table 5-1. Chapter 5 Table of contents.

Table 5-2. Chapter 5 Key points.

- Independent of skill level, meta-stability in practice design was shown to support learning.
- The amount and rate at which learning occurred in a complex multi-articular climbing task was shown to be dependent on the existing skill levels of the climbers.
- Skill was shown to moderate the exploration of affordances where lower skill level involved greater exploratory actions.
- The transfer of skill was shown to be supported by practice effects induced under meta-stable practice conditions in experienced individuals.
- The successful transfer of skill in inexperienced individuals was supported by exploratory behaviours. That is, during transfer, inexperienced climbers showed higher levels of exploratory actions and lower levels of entropy, whereas at the beginning of practice high exploration and high entropy was observed.

Abstract

Previous investigations have shown that inducing meta-stability in behaviour can be achieved by overlapping affordances through task constraints manipulation, allowing cooperative and competitive tendencies to functionally coexist. The purpose of this paper was to test a number of conditions applying these design principles on performance during skills practice and transfer. Of additional interest, was whether the existing skill level of the participants interacted with the environmental properties of the experimental tasks (varying indoor climbing routes). Two skill groups practised on three routes per session over four separate sessions. At the end of the final session, climbers undertook a transfer test. Routes, matched for difficulty, were different in terms of hand-hold design. Route-1 and Route-2 were designed with holds with a single graspable edge. Route-3 had at each hold, two graspable edges. Behavioural exploration at the level of the hip and hand was shown to be largest under the designed meta-stable conditions (Route-3). Skill level also interacted with specific route properties during practice, influencing the nature of transfer of climbing performance, with data suggesting meta-stability can support the transfer of skill through causing an increasing in exploratory behaviours during practice.

5.1 Introduction

Inducing learning can be facilitated by challenging the equilibrium of stable movement patterns to favour other movement patterns that need to be learned (Teulier & Delignières, 2007) and by allowing the individual to utilise existing skills from which to explore new and potentially better solutions (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003). This study investigated how this process may be facilitated under conditions of meta-stability (Pinder, Davids, & Renshaw, 2012). Meta-stable movement coordination regimes refer to regions of performance where individual and environmental influences on performance simultaneously coexist. This leads to the coexistence of competitive (less stable) and cooperative (more stable) coordination tendencies where neurobiological components support adaptation and emergence of new behaviours (Kelso, 2012).

Previous investigations have shown that individuals can be positioned to perform under a meta-stable regime by manipulating constraints so as to create an overlap in different opportunities for action (affordances) (Hristovski, Davids, Araújo, & Button, 2006; Pinder et al., 2012). For example, Hristovski et al. (2006) observed that learning designs which altered the (arm)scaled distance of boxers to a punch bag during practice facilitated affordances to constrain the emergence of a rich range of hitting actions. These results showed that a feature of practice in a meta-stable regime is for different patterns of movement coordination to be explored spontaneously during practice (Hristovski et al., 2006). Although the mechanism for inducing meta-stability appears to be conceptually understood, the impact of practice in this system state is unclear. For instance, whilst exploration of different actions can emerge under novel practice task constraints in inexperienced individuals (Chow, Davids, Button, & Rein, 2008), experienced individuals under similar constraints show minimal exploration (Chow, Davids, Button, & Koh, 2006; Seifert, Wattebled, et al., 2014). One of the distinguishing features of experienced individuals in multi-articular tasks is an immediate availability of stable movement patterns which support a functional response to satisfy interacting task and environmental constraints (Seifert, Komar, et al., 2014; Seifert, Wattebled, et al., 2014).

An important feature of acquiring skill in multi-articular tasks is that different actions can be adopted within and across individuals for achieving the same performance outcomes, reflecting the inherent degeneracy of the movement system (Mason, 2010; Seifert, Wattebled, et al., 2014). Through a process of managing energy that constantly flows into open systems under dynamic equilibrium, the nervous system exploits degeneracy during self-organization to maintain stability by dissipating energy to a manageable degree (Tononi, Sporns, & Edelman, 1999). This system tendency satisfies a basic organismic constraint of movement efficiency (Newell, 1986). A useful indicator of the relative level of a system's stability is the degree of entropy that it exhibits (Edelman & Gally, 2001). Low levels of entropy suggest behavioural certainty and stability (observed in straight forward and fluent performance behaviours) whilst, higher levels of entropy indicate behavioural uncertainty and instability (more complex, chaotic and less fluent movements, (Cordier, Mendès-France, Pailhous, & Bolon, 1994)).

In this study, experimental design was manipulated to induce meta-stability in performance of a complex motor coordination task to observe exploratory behaviours in experienced and less experienced individuals. Meta-stability was represented in an indoor climbing task by increasing the number of available climbing affordances in the environment, allowing their usability to overlap. In the task of climbing, affordances refer to properties of a wall that are perceived by individuals for supporting grasping and climbing actions that are also experience-dependent (Boschker, Bakker, & Michaels, 2002). Importantly, even novice climbers can perceive climbing affordances if they are within their ability level (Pezzulo, Barca, Bocconi, & Borghi, 2010), suggesting the potential to transfer fundamental skills such as ladder climbing to novel climbing environments based on the combined route and hold design properties (Bläsing, Güldenpenning, Koester, & Schack, 2014). In this study, overhand- and side-orientated grasping actions were supported by modifying the number of edges and orientation of hand holds. Overhand grasping actions were supported by designing holds with a graspable edge that ran parallel to the ground. Vertically-aligned grasping actions were supported by designing holds with graspable edges that ran perpendicular to the ground. It was anticipated that meta-stability would emerge in climber-environment systems if, at each hold, both an over-hand and a vertically-aligned grip were available (note that a number of pilot studies have been undertaken in support of these assumptions, see (Seifert, Orth, et al., 2014; Seifert, Orth, Hérault, & Davids, 2013)).

The hypotheses included: 1) all groups would be induced to learn on a route where, at each hold, multiple actions were functionally available; 2) less experienced performers would show learning on routes where only a single action was supported, that was specific to climbing, whereas more experienced climbers would not; and 3), that transfer of skill would be facilitated by practicing under the various conditions.

5.2 Methods

5.2.1 Participants

A total of 14 participants were recruited based on their self-reported red-point levels (where red-point refers to route climbing ability after practice). One group comprised participants (n=7) with a level 5b-5c on the French rating scale of difficulty (F-RSD). A second group of seven individuals were recruited on the basis of having a level between 6a-6b (Draper, Canalejo, et al., 2011; Draper, Dickson, et al., 2011). Participants provided informed consent and the study conducted with ethical approval.

5.2.2 Experimental Procedure

Data were collected on four separate days, with at least two days separating each session. All sessions started with participants being fitted with a harness and climbing shoes. After a climbing-specific warm up, they completed three previewed, top-roped climbs. Each climb was on a different experimental route, the order of which was counterbalanced. Between each climb, a seated 5-minute rest was enforced. On the fourth session, climbers also undertook a transfer test at the end. For each climb participants were instructed to self-pace their ascent, with the following task-goal: explore the way to climb in the most fluent manner, i.e., without falling down and by minimizing pauses in the rate of body displacement vertically on the wall surface.

5.2.3 Instrumentation

Participants were equipped with a luminous marker positioned on the harness at the body midline. Video footage of each ascent was captured with a frontal camera (Sony EX-View Super HAD, Effective pixels:768x520, that allowed a resolution of 560 lines, with a 2.6mm lens that offered a 120° angle of view), fixed 9.5m away from the climbing wall and at a distance of 5.4m from the ground. A calibration frame, 10.3m vertical x 3m horizontal and composed by 20 markers, was used to correct for distortion and calibrate the digitized trajectory from pixels to metres (completed using a supervised tracking procedure with the Kinovea 8.15 software).

5.2.4 Behavioural data

Behavioural data that reflected learning in the form of exploratory activities were collected in analyses of hand and hip movements. Specifically, exploration was indexed using: (i) the total number of exploratory actions with the hands (where a hold is touched by the hand, and during this contact not subsequently used to move or weight the body and the next action of the hand was either to move to another hold or to release the hold and then change the hand's position on the same hold; and (ii), the geometric index of entropy (GIE), calculated from the trajectory of the climbers' hip (using the 2D trajectory of an LED positioned at the hip mapped onto the plane of the climbing wall during each ascent).

The GIE is calculated by taking the logarithm to the base of the distance of the path covered by the hips (L) divided into the perimeter of the convex hull around that path. Noting that the outcome is then divided by the natural logarithm (log^2) to place GIE in dimensionless terms (detailed in Sibella, Frosio, Schena, & Borghese, 2007). According to Cordier, Mendés-France, Pailhous et al. (1994) the GIE measure can assess the amount of fluency of a curve. The higher the entropy value, the higher the disorder of the climbing trajectory. Skilful climbing can be reflected in a low entropy value because it is associated with a low energy expenditure, less variation in acceleration, and use of more technically advanced actions (Sibella et al., 2007). When considered over successive trials GIE is also a useful measure of learning because of it relates to the degree of complexity of route finding behaviours (Boschker & Bakker, 2002; Cordier et al., 1994), indicating the ability of climbers to pick up information from a surface to find paths through the route that afford fluid continuous traversal (Cordier et al., 1994). Pijpers and colleagues (Pijpers, Oudejans, Bakker, & Beek, 2006) also distinguished between exploratory and performatory movements as pertaining to the level of coupling between a climber and a climbing environment, revealing behavioural certainty with regards to hold use. Climbers tend to reduce the time spent in states of three-limb support because it increases the force required at other limbs to remain fixed to the wall (Bourdin, Teasdale, & Nougier, 1998; Sibella et al., 2007), limiting exploration to instances of uncertainty. Additional data on other variables were also collected related to performance: (number of falls) and the use of hand holds (ratio of number of holds used to holds contained in the route).

5.2.5 Routes

Three experimental routes were designed based on the orientation and number of graspable edges at each hold (20 holds per route were used). Route-1 contained only holds with a horizontally-graspable edge. Each hold in Route-2 had a single, vertically-graspable edge and, Route-3 included at each hold a graspable edge that was horizontally aligned in addition to an edge that was vertically-graspable. This latter route was considered to represent meta-stability as it afforded the choice of two grasping actions at each hold i.e. those actions supported by Route-1 and Route-2 (see Figure 5-1 for details). The transfer route (Route-4) was made up of six horizontal holds, and seven vertical holds, as well as seven holds with both edges. The transfer test was designed to determine whether learning was transferred and whether it could be related to behaviours induced under the various practice constraints. The transfer route was also designed to represent the different constraints on practice. Each route was designed by an experienced setter and the difficulty level held constant at level 5b F-RSD. The ratings were confirmed by consensus with two other route setter.

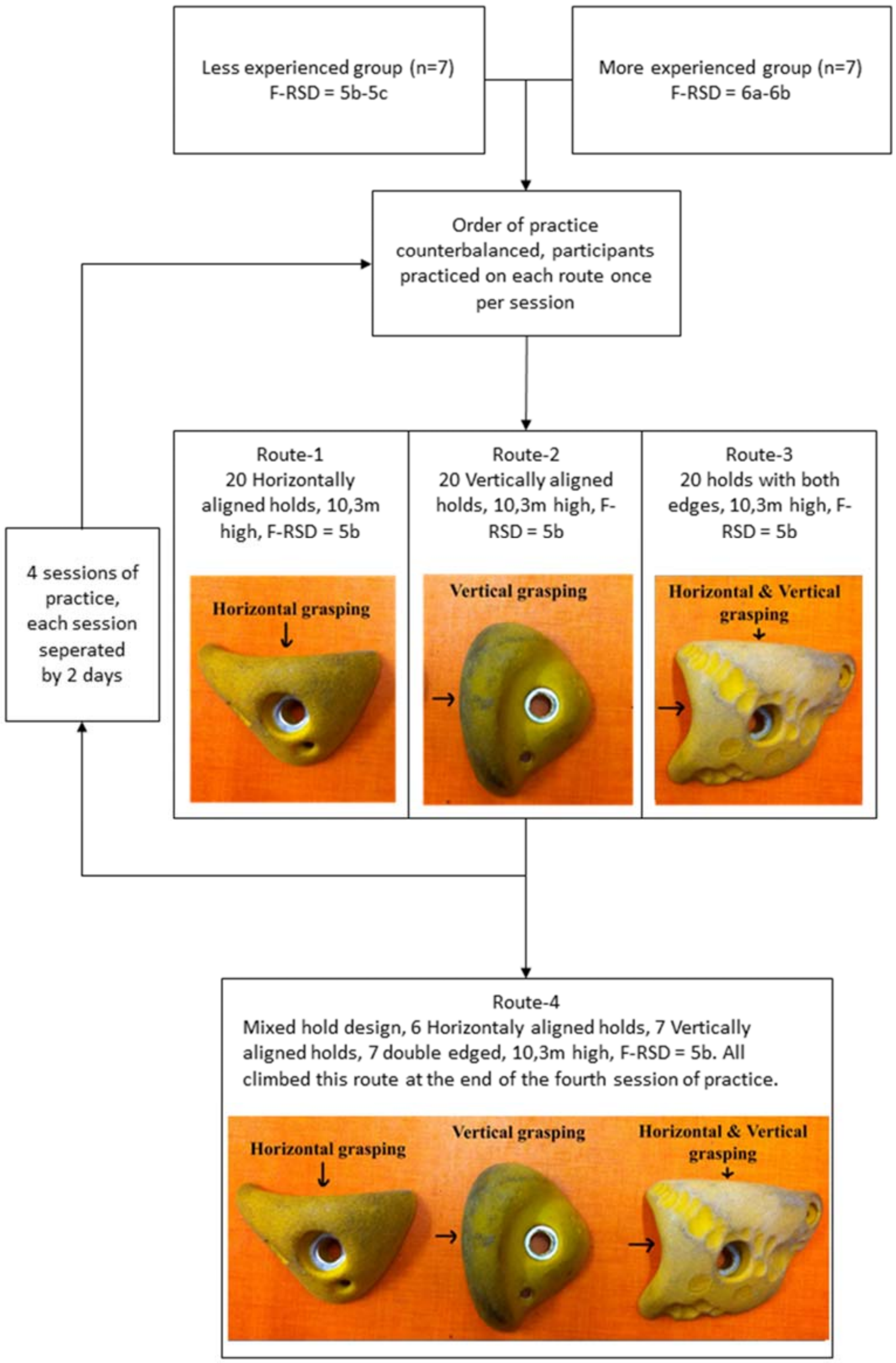

Figure 5-1. Experimental design. Orientation and shape of the holds for the experimental routes.

In Figure 5.1 the arrow indicates the preferential grasping allowed by the hold design. Route-1 was designed using holds graspable with an overhand grip. Route-2 was designed using holds graspable along the vertically aligned surface. Route-3 was designed using holds that each were graspable horizontally and vertically. The transfer test included all three types of holds.

5.2.6 Data analysis

A mixed methods ANOVA for the trial (4) x route (3) x group (2) effects were used to evaluate the learning effect separately for the entropy and hand-hold exploration data. Prior to undertaking the analysis, Mauchley's test was used to confirm homogeneity of sphericity for the repeated measures. For explaining the size and nature of differences, as well as interaction effects, planned contrasts were then performed. Following effects are reported significant at $p \leq .05$, noting that effect sizes were only calculated from contrasts and main effects that involved a single degree of freedom, see (Kirk, 1996)), and according to:

$$r = \sqrt{(F(1,df_R)/F(1, df_R)+df_R)}$$

Where df_R refers to the degrees of freedom of the residual term.

Equation 5-1. Effect size for contrasts.

Contrasts were designed with the expectations that entropy values and hold exploration would reduce with practice, that more complex route design would increase entropy and hold exploration, and that more experienced climbers would display lower entropy and hold exploration. Of particular interest was whether interaction effects between route, trial number and skill would emerge to suggest that skill level interacted with specific route design properties, influencing whether or not learning was induced. For follow-up tests, Bonferroni adjustments controlled for inflation of the type I error. Being based on categorical data, instances of falls were assessed using non-parametric tests

(Freidman's and Wilcoxon's) and the data with respect to the number holds used, relative to those available, were assessed with repeated measures ANOVA.

To assess transfer, an omnibus of t-tests was planned on both variables at the within- (between Trial 4 on the double-edged route and the transfer route) and between-group levels of analysis (less experience vs. more experience) with Bonferroni adjustments.

5.3 Results

The following result section is organized in relation to the key hypotheses of interest, that: 1) both groups would be induced to learn on the meta-stable route; 2) the less experienced group would show learning on routes that require climbing specific experience, whereas, the more experienced climbers would not; and 3), that transfer of skill would be supported in both groups.

In examining the descriptive data summarised in Figure 5.2, the outcomes suggest that for both groups learning effects were evident in the GIE. However, for hand-hold exploration only the less experienced demonstrated exploratory behaviour that appeared to reduce during practice. Furthermore, the two groups appeared to differ in terms of which route induced a learning effect in entropy. Specifically, the experienced group appeared to show a learning effect only on the double-edged route (emphasised using the line fit). For the less experienced group, learning was evident across all conditions but, with a slightly reduced effect of practice on the horizontal-edge route. Finally, the data also suggests that both groups could transfer skill in terms of climbing fluency to the new route, however, notably, the less experienced group showed an increase in exploratory behaviour.

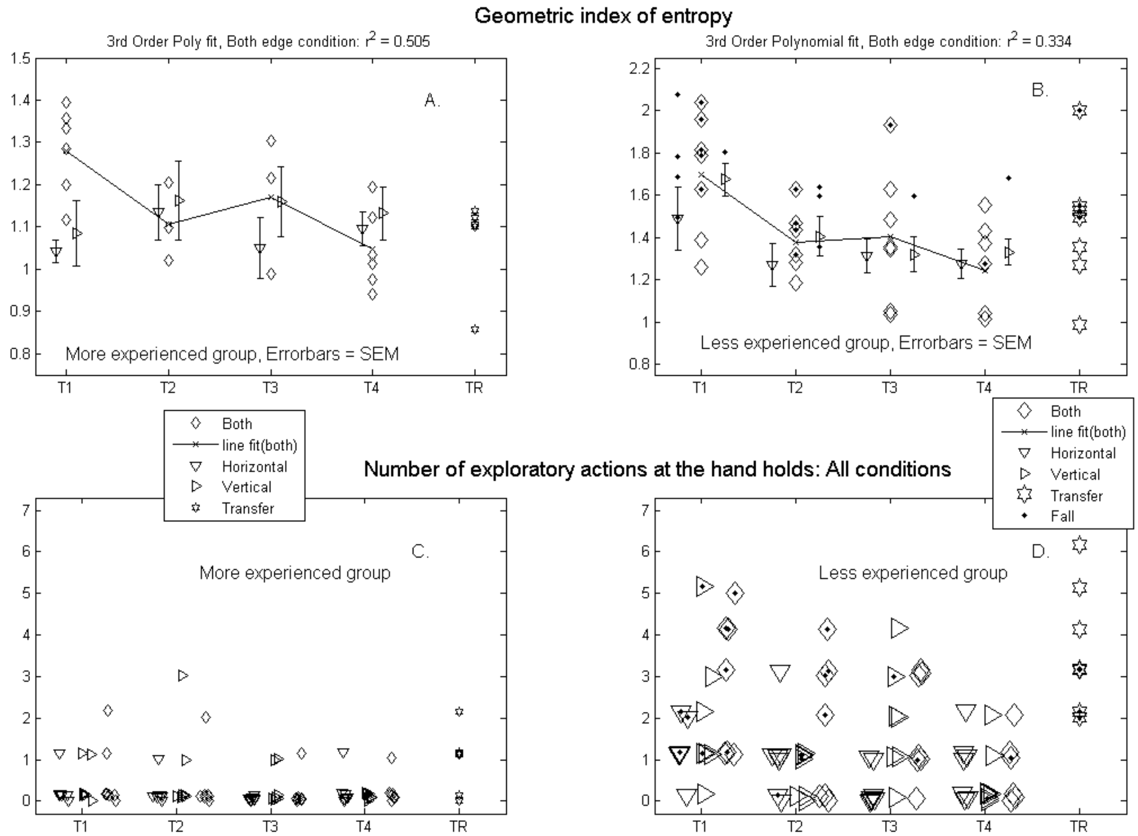

Figure 5-2. The entropy and hand hold exploration across each condition, over practice and under transfer as a function of skill level. **SEM** = standard error of the mean; **T** = trial. **TR** = transfer test.

Of additional interest was that some of the beginner climbers fell during practice and under transfer (filled in markers in Figure 5.3). Interestingly, under transfer, the climbers who showed the worse fluency (i.e. higher entropy) also showed lower exploratory actions. In examining the data at the first trial of practice, however, it can be seen that individuals with the best fluency exhibit lower amounts of exploratory behaviour. This relationship is highlighted in Figure 5.4 below and suggests that one of the effects of practice uncovered in the transfer test was that beginners learnt to explore without negatively impacting on their climbing fluency.

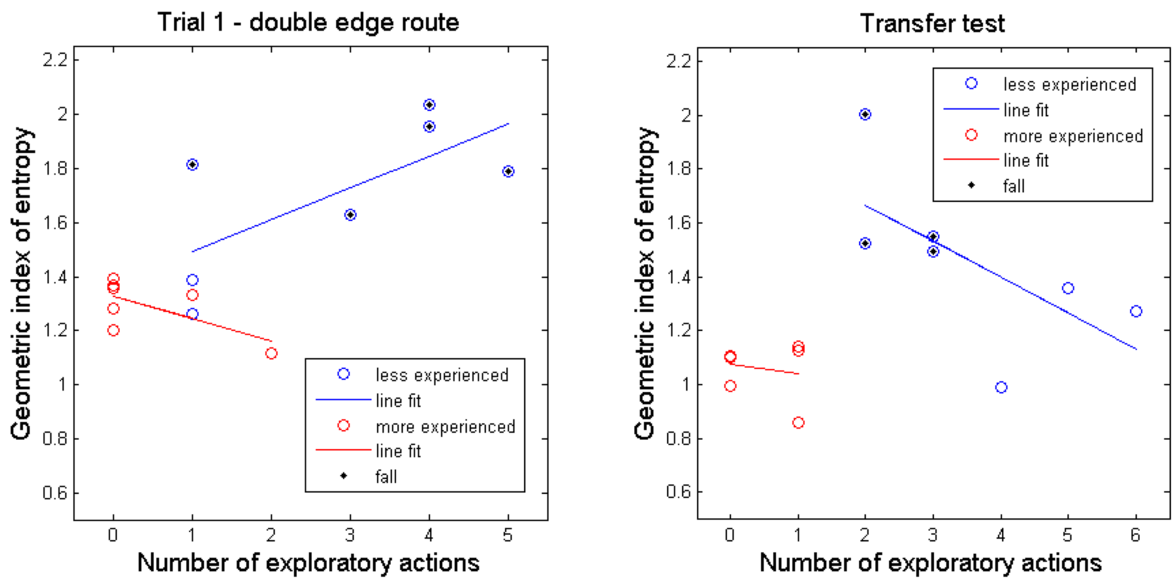

Figure 5-3. Exploration relative to entropy at Trial 1 in the double edged route and in the transfer test.

5.3.1 Mixed methods ANOVA with contrasts

5.3.1.1 Effect of practice on meta-stable route

The mean values and their respective standard errors of the mean, and significant main effects and interaction effects are summarised in Figure 5.4 where in Panel A, Graphs A-E refer to the analysis of entropy of the hip trajectory and in Panel B, Graphs F-J relate to hand hold exploration data. There were significant interaction effects at both the route x practice and group x practice level for the outcome of entropy: $F(1, 12) = 2.274$, $p = .05$, $r = .40$; $F(3, 36) = 6.256$, $p = .002$, respectively. However for the outcome of hand exploration there was only a significant interaction at the group x practice level; $F(3, 36) = 3.323$, $p = .03$. In examining the estimated marginal means for entropy and hold exploration for the route by practice interaction (Figure 5.4, graphs D and I respectively) it is clear that the less experienced climbers showed a distinct global learning effect whereas the more experienced climbers did not. For the condition by practice effect, the marginal means show that primarily for the double edged and vertical routes there was a distinct trend from higher to lower amounts of entropy and hand exploration observed with practice (Figure 5.4, graphs E and J respectively). In order to determine whether both groups showed a learning effect on the double-edged route, follow up tests were undertaken where repeated measures ANOVA were used for each condition across each group (summarised in Table 5.3).

In summarising the significant findings shown in Figure 5.4. Panel A, Graphs A-E, summarise entropy and Panel B, Graphs F-J summarise hold exploration. Graph A and Graph F indicates the overall effect of experience (less vs. more) on entropy, $F(1, 12) = 8.06$, $p = .015$, $r = 0.634$, and hold exploration, $F(1, 12) = 14.30$, $p = .003$, $r = 0.74$, respectively. Graph B and Graph G indicates the overall effect of Route design on entropy, $F(2, 24) = 6.970$, $p = .004$, and hold exploration, $F(2, 24) = 4.024$, $p = .02$, respectively. Graphs C and H indicates the overall effect of trial on entropy, $F(3, 36) = 8.127$, $p < .001$, and hold exploration, $F(3, 36) = 5.133$, $p = .005$, respectively. Graphs D and I indicates the interaction effects between practice (over four trials) and experience level (less vs. more) on entropy, $F(3, 36) = 6.256$, $p < .002$, and hold exploration, $F(3, 36) = 3.323$, $p = .03$, respectively. Graph E and H indicates the interaction effect for entropy, $F(1, 12) = 2.274$, $p = .05$, $r = .40$, and hold exploration, $F(1, 12) = 2.867$, $p = .08$, $r = 44$, respectively.

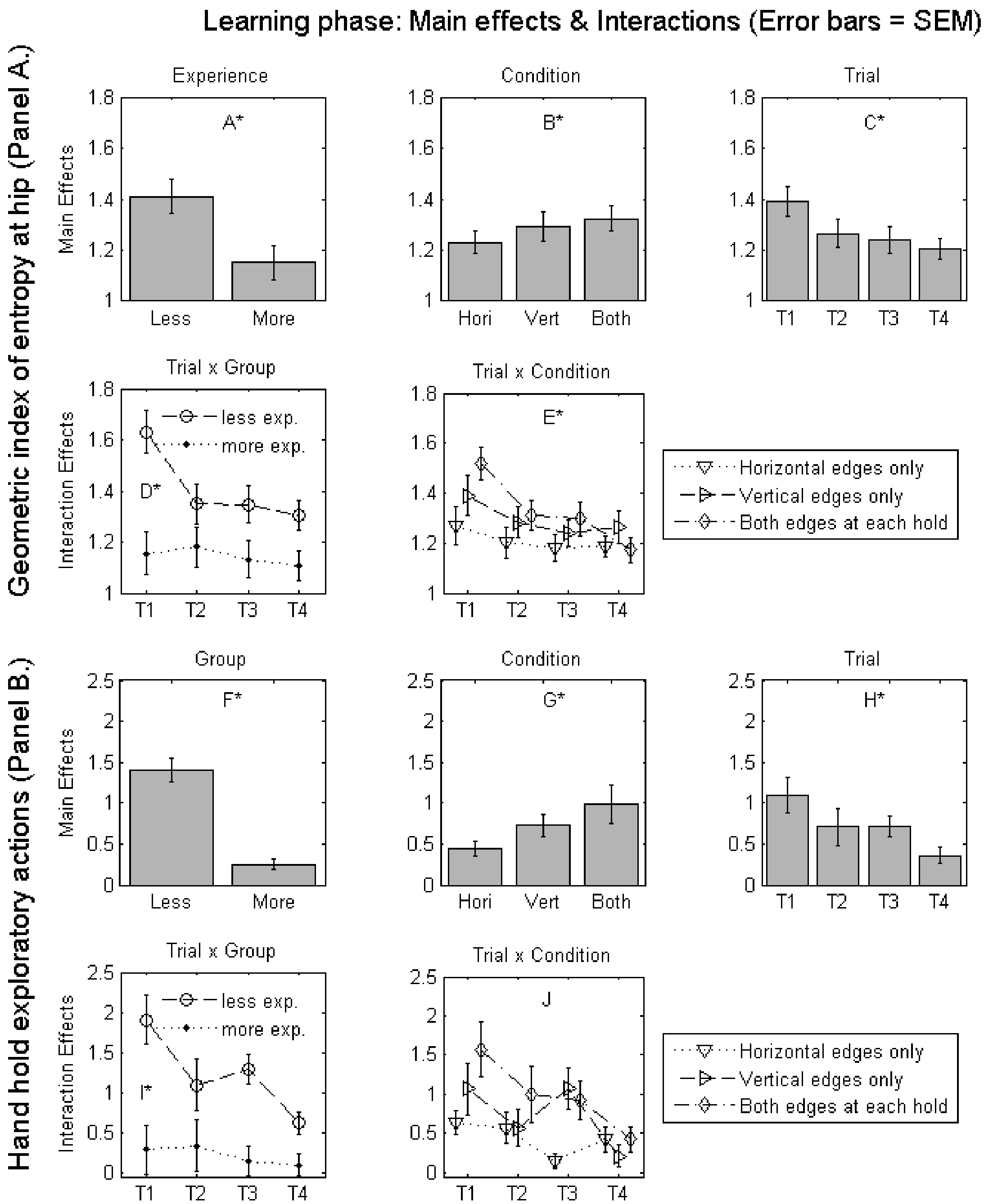

Figure 5-4. The main and interaction effects for entropy and hold exploration. **Both** = Double edged route; **exp.** = experience; **Hori** = Horizontal route; **SEM** = standard error of the mean; **T** = Trial; **Vert** = Vertical route; * = significant effect.

5.3.1.2 Effect of route design and skill on learning

The findings shown in Table 5-3 also support the hypotheses that existing participant skill levels determined whether a specific route induced learning or not. In the more experienced group neither the horizontal route, F(3, 18) = 1.347, p =.291, nor the vertical route, F(3, 18) = 0.987, p =.421, induced learning, whereas the double edged route showed a significant learning effect with regard to entropy (Table 5-3). There were no significant effects related to hand hold exploration across any route in the experienced group. In contrast, in the less experienced group, both the double edged route and the vertical edged route, F(3, 18) = 6.552, p =.003, induced learning, whereas the horizontal edged condition showed no significant effect, F(3, 18) = 1.574, p =.230. Similar to the double edged route, on the vertical edged route, the planned contrasts showed that entropy was significantly higher at Trial 1 compared to Trial 4, F(1, 6) = 5.847, p = .052, r = .703.

Wilcoxon's tests also showed that no route was associated with having a significantly greater probability of falls compared to any other. There were 4 falls on the horizontal route (across 28 trials of practice per route), 7 on the vertical route and 13 in total on the double edged route. Although these results were not significant overall, the greater number of falls on the double-edged route are, none-the-less, meaningful. At the level of practice, there were 10 falls at Trial 1 (from a possible 21 total), 8 falls at Trial 2, 4 falls at Trial 3, and 2 falls at Trial 1 (raw data can be viewed in Figure 5.3, Graphs B and D). It can also be noted that Wilcoxon's test between Trial 1 and Trial 4 showed a significant reduction of falls, z = -2.00, p = .046 when considering only the effect of practice.

Table 5-3. Follow-up statistics of the learning effect across each route for each group on entropy and hand hold exploration.

Variable	Group by condition	Trial 1		Trial 2		Trial 3		Trial 4		
Entropy	**More Exp**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Repeated measures ANOVA**
	Horizontal	1.04	0.07	1.14	0.18	1.05	0.19	1.10	0.11	F(3, 18) = 1.347, p =.291
	Vertical	1.08	0.20	1.16	0.25	1.16	0.22	1.13	0.17	F(3, 18) = 0.987, p =.421
	*Both**	1.26^	0.11	1.16	0.12	1.13	0.13	1.05	0.09	F(3, 18) = 6.258, p =.004
	Less Exp									
	Horizontal	1.50	0.40	1.27	0.27	1.31	0.21	1.28	0.18	F(3, 18) = 1.574, p =.230
	*Vertical**	1.70^	0.37	1.41	0.22	1.32	0.17	1.40	0.31	F(3, 18) = 6.552, p =.003
	*Both**	1.70^	0.29	1.38	0.15	1.41	0.32	1.25	0.23	F(3, 18) = 5.820, p =.006
Touches	**More Exp**									
	Horizontal	0.14	0.38	0.14	0.38	0	0	0.14	0.38	F(3, 18) = 0.391, p =.761
	Vertical	0.29	0.49	0.57	1.13	0.29	0.49	0	0	F(3, 18) = 1.079, p =.383
	Both	0.43	0.79	0.29	0.76	0.14	0.38	0.14	0.38	F(3, 18) = 0.344, p =.794
	Less Exp									
	Horizontal	1.14	0.69	1	1	0.29	0.49	0.71	0.76	F(3, 18) = 1.895, p =.167
	Vertical	1.86	1.68	0.57	0.54	1.86	1.35	0.43	0.79	F(3, 18) = 3.138, p =.051
	*Both**	2.71^	1.70	1.71	1.70	1.71	1.25	0.71	0.76	F(3, 18) = 7.000, p =.003

*significant effect accounting for the six comparisons per outcome variable (required alpha level set at 0.006)

^Contrast relative to Trial 4 for the same condition was significantly different

Exp = experience

5.3.1.3 Transfer effect

To understand the impact of learning and skill on behaviour during transfer, comparisons were undertaken on entropy values and hand hold exploration (summarised in Table 5-4). The key findings revealed that: a) neither entropy, nor hand hold exploration, significantly distinguished between groups at the final trial of practice on the double edged route; entropy was not significantly different between groups (less experience vs. more) or between conditions (trial 4 on the double edged route vs. transfer route) were significantly different; c) only hand exploration distinguished between the two groups (less vs. more) under the transfer test conditions, $t(12) = 4.47$, $p = .001$, $r = .79$; and finally d), in the less experienced group, hand hold exploration significantly increased under transfer conditions relative to the amount exploration on the fourth trial of practice on the double edged route, $t(6) = 4.804$, $p = .003$, $r = .89$. This observation suggests that the experienced group transferred behavioural organization, which supported low entropy and low hand hold exploration after practice. In contrast, the less experienced group only showed a capacity to transfer climbing fluency and, it was the two outcome variables, entropy and hand-hold exploration, in combination that differentiated the two groups under transfer conditions.

Table 5-4. T-test omnibus of between group and within the group effects on entropy and hand hold exploration. Specifically trial 4 of the double edged route and the transfer route were tested.

Variable	Group	Double-edge route (T4)		Transfer route		
		Mean	SD	Mean	SD	Paired t-tests (2-tailed)
Entropy	**More Exp**	1.096	.155	1.185	.315	1.222(6) p = .27
	Less Exp	1.248	.226	1.456	.310	2.243 (6) p = .07
Independent t-tests (2-tailed)		1.45(12), p = .17		1.62(12), p = .13		
Touches	**More Exp**	0.143	.378	0.714	1.512	2.828(6) p = .03
	Less Exp	0.714	.756	3.571	.756	4.804(6) p = .003*, r = .89^
Independent t-tests (2-tailed)		1.79(12), p = .10		4.47(12), p = .001*, r = .79^		

*Significance adjusted for the eight comparisons (required alpha level set at 0.006)

^$r = \sqrt{(t^2/t^2+df)}$

Exp = experience

5.4 Discussion

The purpose of this study was to understand the interactions between prior experience and practice condition on learning climbing fluency as it pertained to practice effects and transfer. The first hypothesis, that learning could be induced using meta-stable design principles was confirmed, regardless of the initial skill level of the individuals. The evidence suggests that at the hip level, a similar mechanism across skill levels was driving learning in the meta-stable condition. At the level of the hand activities, a potentially differential effect was uncovered in that the less experienced climbers showed greater levels of hand hold exploration compared to the more experienced climbers. The second hypothesis was also confirmed, with data suggesting that the existing experience level of the participants interacted with specific route design properties, influencing the nature of the transfer of skill to each practice condition. Findings suggesting that knowledge of the vertically-orientated grasping pattern of coordination needs to be acquired through experience.

Finally, the third major question in this study was also addressed: transfer contexts designed to represent similar levels of environmental variability, as those experienced under practice constraints, can facilitate the transfer of skill. Of additional interest was that the nature of transfer was found to have a structure that was only revealed by considering the two outcome variables, entropy at the hip and hand hold exploration in combination, suggesting that the initial level of skill of individuals prior to practice, influenced the nature of the transfer of skill after practice. For the less experienced climbers, a significantly higher amount of hold exploration combined with low entropy suggests that the transfer of skill was facilitated by hand hold exploration.

5.4.1 Meta-stable environmental design properties induces learning in less and more skilled individuals

The data showed that both groups were induced to go through a learning process (a general improvement in performance) when practising on the route that supported, at each hold, a choice of grasping actions, one choice supporting an over-hand grip and one that supported a vertical-hand grip (see Table 5-2, and refer back to the learning curves in Figure 5-2, Graphs A and B). Noting the shape of the learning curves at the hip, it appears that the behavioural changes shared a similar nature. However, at the hand level, exploratory activities were very different between groups (Figure 5-2, Graphs C and D). The less experienced climbers exhibited much greater levels of touching, but not grasping holds (Figure 5-2 Graph D). This finding suggests the double edged condition may have induced learning in both the experienced and the less experienced individuals which supported more fluent route finding under transfer conditions.

There was also an indication of a skill-dependent effect, related to the larger amount of hand hold exploration shown by the less experienced group compared to the more experienced group. These data suggest that haptic (and perhaps, therefore, visual perception) of how to grasp and/or use holds were being challenged during practice in the less experienced group. In the more experienced group, it seems the overt haptic exploration was unnecessary, probably, because the capacity to perceive information related to hold graspability had already been adapted through experience (Bläsing et al., 2014; Boschker et al., 2002; Pezzulo et al., 2010). An interesting question for future research is that one reason the less experienced climbers needed to explore more with the hands was that their ability to pick-up visually available information were also underdeveloped. It is also possible that the experienced climbers were induced to learn at the visual level under the meta-stable route practice conditions.

5.4.2 Environmental design properties interact with the intrinsic dynamics of individuals to shape the nature of learning

The prior experience levels of the participants interacted with the route type, suggesting the climbers prior experienced influenced the transfer of learning to each practice condition (transfer of learning referring the effect of prior skill on the rate of learning). The vertical and horizontal routes did not induce learning in the experienced group. In contrast, the vertical *and* double edged routes induced learning effects in the less experienced group (see Table 5-2 and Figure 5-2, Graphs B and D).

These results, suggest that the grasping actions associated with vertically aligned edges during route finding appeared to require experience to stabilize. On the other hand, the grasping actions for horizontally aligned holds appeared to be easier for less experienced individuals utilise. The less experienced climbers' transfer of skill to the horizontal route can be explained as a function of these grasping opportunities matching fundamentally stable grasping actions, such as ladder climbing. This result is similar to other findings showing that inexperienced individuals climbing ice-falls tended to adopt a similar movement pattern where the symmetrically-organised body resembles an X-shape (Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013).

Notability, in the less experienced group, the vertical and double edged route induced fairly similar amounts of exploration at both the hand and hip levels. It was expected that the double edged route could facilitate greater exploration with the hands simply by virtue of there being more edges. For example, on the double edged route, the use of more unstable vertical grasping actions could have been explored whilst falling back to the use of the more stable horizontal actions, yet this opportunity was not exploited to a large effect. Additionally, a similar level of hand hold exploration was occurring on the vertical edged route, which in contrast, had half the number of edges. The finding that both the vertical and the double edged route induced similar levels of exploration suggests that the need to stabilize vertical grasping was driving haptic exploration, but was possibly limited by the balancing exploration with fatigue. Indeed both conditions (vertical and double) entropy reduced with no significant differences between conditions. However, as practice continued, hand hold exploration remained significantly elevated on the double route with a significant route by trial effect. This observation suggests that, as the route finding problem was relaxed, hold exploration levels were sustained in the double edged route.

Future research should consider in what way exploratory actions are functional during practice. When a climber stops and explores a hand hold this is believed to be costly energetically (Sibella et al., 2007), hence, it would be anticipated that exploration should reduce once the route finding problem is resolved. Given that exploratory behaviour remained elevated in the double-edged condition it is possible that the individuals either took advantage of the opportunity to explore the hand-holds graspability explicitly intending this, or, alternatively, ongoing residual effects of practice under the meta-stable conditions continued to promote exploration at an implicit (sub-conscious) level.

5.4.3 Meta-stable practice constraints supports the transfer of skill in multi-stable movement systems

In accounting for the ability of the experienced group to transfer climbing fluency, there can be two possible explanations. One is that because the transfer route was composed of holds with characteristics of each of the three routes. Because the climbers had practised on all three routes they were more effectively prepared for performance on the transfer route. An additional interpretation is also supported in that it was the learning effect induced on the double edged route that supported the ability of the climbers to transfer. Because the transfer route was new, it would be expected that the experienced climbers would exhibit similar levels of performance as the first trial of practice on the double-edged route. However, since the double edged route was the only route to have induced a learning effect, this suggests that it was the effect of practice on the double route that facilitated transfer in the more experienced climber. Future research should, however, to confirm this, observe different groups practice exclusively on a single type of route.

5.4.4 Exploration supports the transfer of skill picked up during practice

The less experienced climbers also showed a capacity to transfer climbing fluency at the level of the hip but in contrast to the more experienced climbers, they exhibited a large amount of hand hold exploration on the transfer test. This was surprising because early in practice, both hand hold exploration and hip entropy were high, whereas in transfer, high hand hold exploration was associated with low entropy. This finding suggests the possibility that exploration at the level of the hand supported the transfer of route finding in the less experienced climbers. And indeed, the climbers who demonstrated the most exploration during transfer also showed the best climbing fluency and nor did not fall (recall Figure 5-3). This finding is in contrast to the first trial of practice, where the more successful climbers demonstrated less exploration at the hand levels. On the transfer route, in this study, the evidence suggests that the reason climbers effectively transferred performance was because of a functional coupling between exploration at the levels of the hand and route finding.

5.5 Conclusions

The findings from this study suggest that during practice, subsystems related to detecting climbing opportunities, including route finding and the use of hand-holds, evolve at different rates, differentiating between existing ability levels. In this experiment both subsystems were induced to adapt during practice in inexperienced individuals whereas, only at the level of route finding was learning induced under conditions that represented a meta-stable practice design. Furthermore, evidence is provided suggesting that either variable practice conditions or experience on a meta-stable route can facilitate the transfer of skill in a representative learning design context.

In summary, the key findings reported in this study are that, in a task involving climbing practice, learning emerged at different levels, the hands and body. The level and rate at which learning occurred was shown to be dependent on the existing skill levels of the climbers. Skill was shown to moderate the stability of specific climbing affordances (qualitatively distinct grasping orientations). Specifically, learning was induced in a group of experienced climbers by manipulating the number of actions available and not by requiring them to learn new, unfamiliar climbing affordances. This practice design supported the transfer of skill in experienced climbers, which is tentatively, attributed to the learning effect induced under meta-stable practice design. Transfer of skill in inexperienced individuals was also related to more exploratory behaviours and is related to practising under a variety of conditions.

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CHAPTER 6. RESULTS PAPER 2

Skill, its acquisition and transfer in a complex multi-articular, physical activity setting

Table 6-1. Chapter 6 Table of contents.

Table 6-2. Chapter 6 Key points.

• Non-specific climbing experience significantly influences the types of climbing actions spontaneously used in an indoor climbing task. • Experienced climbers modify both mobility and movement complexity to maintain smoothness of hip trajectory during climbing. • Side orientated body-wall coordination states during dynamic movement requires climbing specific experience, whereas, face-wall coordination states can be dynamically used without prior climbing specific experience. • After 7 weeks of practice, beginners were shown to spontaneously acquire new side orientated body-wall coordination states and achieve similar levels of skill transfer as experienced climbers. However, beginners did not learn to modify both mobility and movement complexity to maintain smoothness of hip trajectory in a scanning procedure. • Individuals who are in the early stages of learning in a complex multi-articular climbing task show different learning profiles in the evolution of performance outcomes, including, linear improvement and abrupt transitions.

Abstract

Ecological psychology and dynamical systems theoretical frameworks can be strengthened by evaluating adaptive behaviour under representative task constraints that individuals normally seek to participate. Skill acquisition, involving a process where intrinsic dynamics are destabilized then re-organized, has been observed in bimanual coordination and postural regulation tasks where individuals are required to switch between in-phase and anti-phase patterns. In this study, an ecological context of performance designed to facilitate learning whole body, coordination patterns with respect to an indoor climbing surface is evaluated. The first study sought to determine whether prior experiences influenced the behavioural tendencies of individuals under meta-stable climbing constraints and whether the grasping patterns used were related to climbing performance. Results revealed that prior experience had an influence over the grasping tendencies during climbing, but that these tendencies did not influence performance outcomes. The second experiment in this chapter, therefore, developed a method to evaluate the appropriate level of analysis for observing the emergence of new coordination patterns in a manner that would reflect their relationship to climbing performance. This involved adapting a scanning procedure that required each individual to use different potential modes of climbing coordination. The results showed that both advanced climbers and beginners could adapt to the task constraints to complete the routes. However, beginners who fell, were unable to move at the same time as being orientated with the side of the body with respect to the wall. In the third and final experiment a pre- and post-test intervention design used the scanning procedure and transfer tests to show the effect of practice on the stability of different climbing patterns of coordination in a group of beginners. A group of beginners were shown to transition toward advanced styles of climbing and performance on a transfer test revealed comparable levels of performance to that of the more experienced group in experiment 2. The learning dynamics of the beginners with respect to the intervention strategy broadly support models of skill learning developed in simple tasks.

6.1 Introduction

Whilst a theoretically grounded design of practice constraints is considered an essential part of improving skill acquisition (Chow, 2013; Lai et al., 2014; McKenzie, Alcaraz, Sallis, & Faucette, 1998; Moy, Renshaw, & Davids, 2014), a number of studies have highlighted important challenges to address (Davids & Araújo, 2010; Mann, Williams, Ward, & Janelle, 2007; Travassos et al., 2013). From tradition perspectives, often variability is viewed as dysfunctional, reflecting that the individual is not able to organize behaviour corresponding to a modelled performance state. Reinforcing this perspective are experimental approaches that emphasize the repetition of an ideal movement pattern under fixed conditions, such as of a particular relative anti- or in-phase relationship between limb segments (e.g., Schöner & Kelso, 1988), the speed and accuracy of repetitive finger tapping (Hick, 1952) or required periodic movements between people (Schmidt, Carello, & Turvey, 1990). More recently, such models have been criticised for their reductionist methods, leading to an unsatisfactory treatment of the role that variability in constraints and behaviour in supporting learning processes and goal achievement in settings individuals normally aim to participate (Button, Seifert, O'Donivan, & Davids, 2014; Liu, Luo, Mayer-Kress, & Newell, 2012).

More recently, studies adopting the ecological dynamics framework (a combined ecological psychology and dynamical systems approach) have found many convincing associations between the complexity of the performance setting and behavioural variability functional for goal achievement (Dicks, Button, & Davids, 2010; Fujii, Yamashita, Kimura, Isaka, & Kouzaki, 2015; Orth, Davids, Araújo, Renshaw, & Passos, 2014; Pinder, Davids, Renshaw, & Araújo, 2011; Pluijms, Cañal-Bruland, Hoozemans, & Savelsbergh, 2015; Travassos, Duarte, Vilar, Davids, & Araújo, 2012). The purpose of the experiments described in this chapter was to evaluate the utility of theoretical models drawn from simple tasks in understanding a complex, multi-articular physical activity practice context (specifically indoor climbing).

6.1.1 Skilled behaviour, its acquisition and transfer in complex multi-articular tasks: The ecological dynamics framework

Skill acquisition refers to the relatively permanent changes in the behavioural characteristics of an individual due to experience under a given set of constraints (Newell, 1996). Changes can occur in structural features to support improved skill and in how the individual functionally responds to performance demands. Functional adaptations refer to changes in how information is related to action that support goal achievement and include the discovery of new movement strategies (Boschker & Bakker, 2002). The problem of learning a new skill is conceptualised for the learner as one of adapting existing skills to the new context in order to seek and attune to functional, specifying informational constraints (Araújo & Davids, 2011; Jacobs & Michaels, 2007). These models raise questions of skill transfer processes, where the transfer of skill refers to the influence of prior experiences under a particular set of constraints on performance under a different set of constraints to those where the skills were acquired (Issurin, 2013; Rosalie & Müller, 2013). Specifically, under modified conditions, acquired skills serve as a foundation that the individual learner can use to explore and identify new (in the sense of adapted, (Araújo & Davids, 2011)) coordination patterns and information-movement couplings that can improve performance (Davids, Button, & Bennett, 2008; Newell, 1991, 1996; Zanone & Kelso, 1997).

This suggests that a mechanism underpinning the ability to transfer skill to different conditions is related to the exploration of different movement patterns and the information-movement couplings used to control them (Newell, 1996; Teulier & Delignières, 2007). In other words, learners can explore more effectively by reinvesting coordination patterns available to them (Teulier & Delignières, 2007). Use of movement patterns that are immediately stable helps the individual to reshape their functional perceptual-motor workspace for improving performance (Sporns & Edelman, 1993). Operationally, a scientist introduces constraints such as objects, places and activities designed to influence the information-movement couplings that are used to utilise behavioural opportunities termed affordances (Gibson, 1979). In doing so he/she makes various theoretically-based assumptions about how constraints are meaningful for supporting action (Chemero, 2009). Similarly, in order to support learning of new coordination patterns, practitioners normally adapt task and environmental constraints making assumptions, using experiential knowledge, about how these can support (or inhibit) a reinvestment of the individual's existing skills (their intrinsic dynamics) for exploring information that can support the transition toward new and potentially more effective opportunities for action (Davids, Araújo, Seifert, & Orth, 2015). Newell (1991) referred to information that supports the emergence of new coordination modes as *transitional information*. Whilst in some cases, relying on the intentions of the individual to generate transitional information may be an effective strategy, in other cases it has proven insufficient (Boschker & Bakker, 2002; Chow, Davids, Button, & Rein, 2008; Delignières et al., 1998; Komar, Chow, Chollet, & Seifert, 2014), highlighting the importance of designing constraints that can effectively induce a search for functional coordination solutions (Newell, Kugler, Van Emmerik , & McDonald 1989).

From a complex systems perspective, transitions and the subsequent (re)organization of behaviour emerge spontaneously because of broken symmetry in coordination regimes (Kelso, 2012). In this case, movement variability is functional in the form of fluctuations from within the system that provide a mechanism facilitating a transition to a new state as the system becomes increasingly unstable. In neurobiological systems, coordination tendencies, are constrained by the backdrop of an individual's intrinsic dynamics and emergent coordination regimes (Kelso, 2012; Kostrubiec, Zanone, Fuchs, & Kelso, 2012). Kelso (2012), outlined different coordination regimes that can influence the affordances available to an individual and that include **mono-stability** (where only a single pattern of movement coordination is stable), **multi-stability** (where two or more patterns of movement coordination are stable) and the **meta-stable** regime. Meta-stable regions are far enough from equilibrium that there is the equi-potentiality of different states of organisation, allowing the individual flexibility to differentiate into multiple states (Juarrero, 1999). Consequently the meta-stable regime may promote a functional form of movement variability by assisting individuals to explore different motor behaviours (Kelso, 2012). For the purposes of promoting exploration, when multiple affordances are made to overlap by manipulating constraints, a meta-stable regime of performance can be induced (Hristovski, Davids, & Araújo, 2006; Pinder, Davids, & Renshaw, 2012). Under meta-stable conditions different affordance are more or less explicit in the sense that the information available for perceiving and acting on an affordance more likely to be actualised (Rietveld & Kiverstein, 2014).

Affordances are, therefore, an important source of constraint reflecting information-based relationships between the structural (e.g., limb size) and functional (e.g., movement pattern) aspects of the individual relative to properties in the environment (Gibson, 1979). Because some affordances have stronger attraction in achieving behavioural goals (Withagen, de Poel, Araújo, & Pepping, 2012), they can be observed through behaviour, such as in the various movement patterns that an individual adopts (Araújo, Davids, & Hristovski, 2006). For example in climbing, affordances can reflect hold reachability (when a hold is within reaching distance to an individual), graspability (when a holds surface has edges that an individual can apply friction enough to support their body weight) and usability (when the individual can apply forces to a hold in such a manner to support movement through a route) (Boschker, Bakker, & Michaels, 2002). Thus in climbing, promoting attunement to information that helps individuals to find climbing affordances is dependent on how the practice context is designed relative to the individual. For example, certain tools and significant others, such as safety equipment used to protect the individual from falling can facilitate climbing to the top of a high surface. Additionally, environmental resources, such as holds with different graspable edges, can encourage exploration of different movement patterns that are important for improving ability level in climbing (Boschker & Bakker, 2002).

6.1.2 The current study

Coordination data recorded during performance within meta-stable regimes suggest that numerous patterns of behaviour can spontaneously emerge as a function of interacting constraints (Hristovski et al., 2006) prompting individuals to vary their actions during goal-directed behaviour (Pinder et al., 2012). Additionally, it has been speculated, that the need to adapt to the enhanced variability induced by the meta-stable performance regime may be more representative, or similar to, the performance contexts individuals normally intend to transfer skills acquired under practice constraints. However, currently, meta-stability has only been tested during performance, involving complex multi-articular actions such as striking a heavy bag in boxing (Hristovski et al., 2009) and batting in cricket (Pinder et al., 2012). These studies confirmed that, under a meta-stable performance regime (respectively, distance between boxers' and a heavy bag to-be-intercepted, and the distance between cricket batters' and the bounce of a ball to-be-intercepted). The data implied that individuals vary trial-to-trial their movement patterns to achieve the task-goal. Although these studies showed how during periods of meta-stability, the perceptual-motor system is supported toward reorganization, the questions of designing meta-stable region of performance in perceptual-motor learning is untested. The previous work in Study 1 has shown that in a meta-stable region of climbing performance corresponded to a higher number of exploratory actions (e.g., touched but not used holds), which decreased with practice (Orth, Davids, Herault, & Seifert, 2013; Orth, Davids, & Seifert, 2013, 2014; Seifert, Orth, Herault, & Davids, 2013). It was also shown in Study 1 that learning effects can be induced in experienced individuals despite the absolute route difficulty rating remaining quite low and well within their ability level.

These data suggest that the variability induced by meta-stability may have facilitated the emergence of more adaptive climbing actions. Challenging research questions include the impact of existing skill in a new learning context, whether new functional behaviours can emerge from meta-stable regions and how adapted behaviours relate to performance under transfer contexts (that is, whether the learning design is based on representative constraints). The following study investigated the role of existing intrinsic dynamics on spontaneous behaviours adopted in a climbing task. This experiment was followed up to determine the appropriate level of analysis to understand movement coordination in climbing using a scanning procedure. Finally the learning dynamics were then observed in a group of beginners under training conditions that represented a meta-stable regime. Assumptions that the task was representative were then followed-up by using transfer tests and a scanning procedure after the learning intervention was completed.

6.2 Experiment 1: Can prior experience influence spontaneous coordinated behaviour in a complex multi-articular task?

Performance is predicated on an individual's adaptability, referring to a balancing between stability and flexibly in behaviour (Seifert, Button, & Davids, 2013; Warren, 2006). Stability is a capacity to readily reproduce a performance outcome with a high degree of reliability (Warren, 2006). Movement patterns are stable in that the functional form of the movement is consistent over time, resists perturbation and is reproducible on separate occasions (Warren, 2006). Flexibility is the ability to use alternative coordinative solutions in cases where other movement solutions are no longer feasible due changes in the environment or individual (Ranganathan & Newell, 2013). During performance, maintaining a balance of adaptability supports skilled performance which is defined as the capacity to achieve an outcome with certainty and efficiency (Newell, 1991; Todorov & Jordan, 2002).

Improvements in performance and learning can be achieved by practice in training contexts different from the performance context (Issurin, 2013; Rosalie & Müller, 2012). Different practice variables can influence the transfer of learning in positive (Manolopoulos, Papadopoulos, & Kellis, 2006), neutral (Arnason, Engebretsen, & Bahr, 2005) or negative (Baratta et al., 1988; Bobbert & Van Soest, 1994) respects. Strength training can, for example, stabilize the performance of movement coordination patterns as a function of how muscles that are used to produce the movement pattern are trained (Carroll, Benjamin, Stephan, & Carson, 2001). However, as noted previously, in addition to exhibiting stability, expert movement coordination also shows flexibility (Bernstein, 1967).

Strength provides a good example of general transfer phenomena that can stabilize movement coordination patterns (Carroll, Benjamin, et al., 2001). In overview, optimal transfer between strength and multi-joint coordination tasks is dependent on the characteristics of the training (intervention length, exercise type, weekly volume, intensity, between set recovery time and periodization), opportunities to practice multi-joint coordination tasks concurrently (Bobbert & Van Soest, 1994; Herman et al., 2009; Herman et al., 2008; Kraemer et al., 2000) and the skill level and training history of the trainees (Lamberth, Hale, Knight, Boyd, & Luczak, 2013). There are, however, some reports of negative transfer effects, where increased strength leads to a reduced capacity for refined regulation and control of movement (Semmler & Nordstrom, 1998). The current study sought to evaluate to the impact of prior experience on performance and learning in the complex multi-articular task of indoor climbing. The main question of interested was whether strength related experience could be shown to support a general transfer of skill or learning by improving the level of exploration of unfamiliar constraints. Of additional interest was whether the organization of behaviour under transfer conditions fit predictions consistent with the presence of coordination tendencies.

In climbing tasks, spatial and temporal indicators taken at the level of the hip are a means of assessing the efficiency of climbing behaviour and subsequent learning dynamics. Furthermore, exploratory and performatory actions are also straightforward to observe. Exploratory actions reflecting cases where the individual touches a hold but does not subsequently use it to support body weight, with the following action to either reposition the hand or foot on the same hold or to move to another hold. Futhermore, distinct coordination tendencies have been related to the orientation of hand holds. Specifically, holds that are aligned perpendicular to the ground plane invite grasping the edge with a vertically aligned grip (similar to taking a cup handle) and can induce the body to be orientated side on the wall. On the other hand, holds with edges running horizontal to the ground plane invite grasping the hold with an over-hand grip (similar to taking a ladder rung). Over-hand grasping is more likely to induce a body orientation with frond of the body facing the wall. Thus presenting individuals a choice at each hold, with the possibility of either taking a vertical or overhand grip, can indicate the influence of intrinsic dynamics in climbing tasks and help determine any relationship between behavioral organization and performance. In climbing we anticipated, that, a beginner who has never used a climbing gym before, comes to the task with general climbing experience, such as ladder climbing. Furthermore muscle groups at the back (latissimus dorsi, serratus anterior) are aligned to support a face to the wall body orientation. Similarly, firemen who are trained in ladder climbing, continually practice this task which requires maintaining the body facing the ladder rungs which are designed to be taken in an overhand position. Thus adapting prior experience of ladder climbing to using holds in an indoor climbing gym is likely to invite grasping edges with an overhand grip with the organized in a face-wall coordination pattern. Furthermore, given that firemen are required to meet high physical standards, this may support their ability to explore the novel task context and thus improve performance more rapidly. Experienced climbers on the other hand, tend to be able to use a much broader range of grasping and body-wall coordination patterns and not require extensive practice when faced with tasks a relatively low difficulty level

(Phillips, Sassaman, & Smoliga, 2012; Seifert, Wattebled, et al., 2014) (see the bottom panel in Figure 6.1).

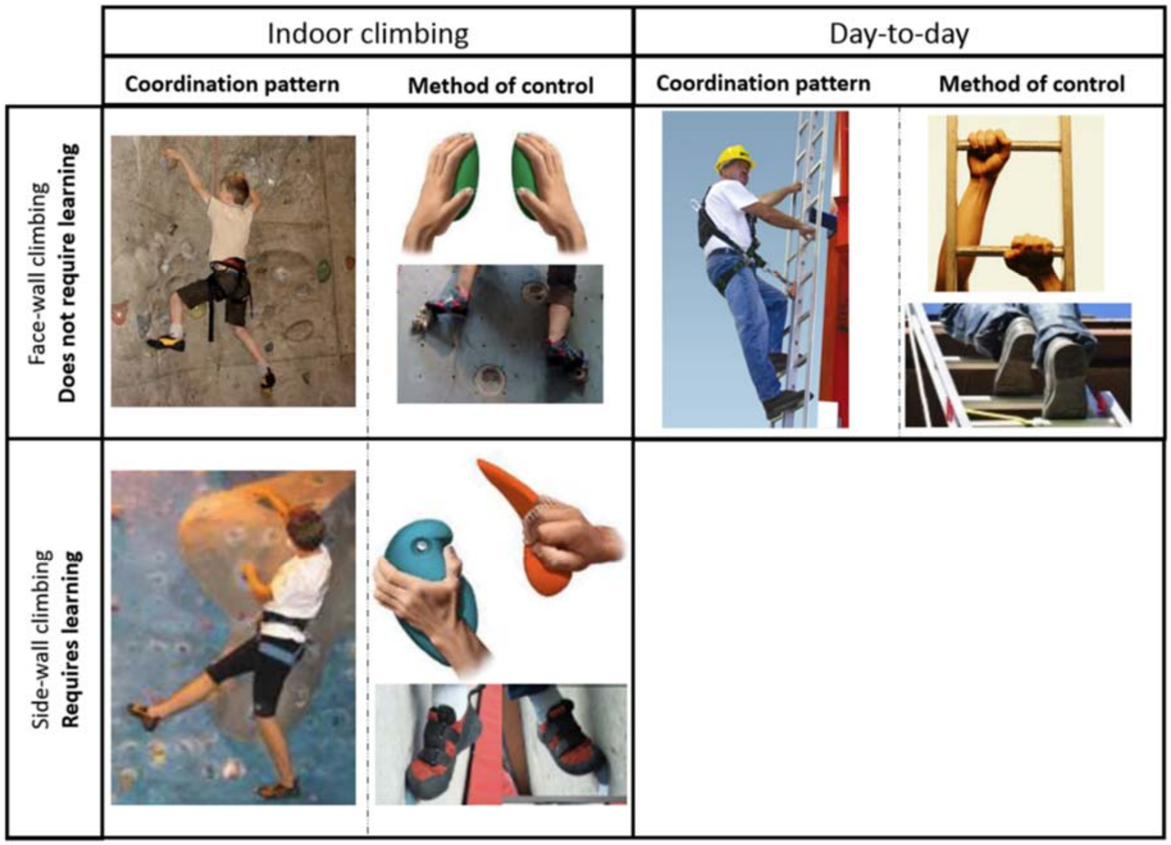

Figure 6-1. Coordination patterns with corresponding grasping actions used in indoor climbing and every day activities.

To test how prior experience of specific actions might affect movement pattern adaptability, three groups with different levels of skill specific experiences were recruited and their spontaneous behaviour were observed on an indoor climbing task designed to support at each hold two grasping opportunities, horizontal and vertical grasping. One group were experienced indoor climbers, another were experienced firemen, and the final group were inexperienced in any particular climbing tasks, acting as a control group. It was anticipated that trained firefighters would demonstrate a significantly stronger tendency to adopt over-hand grasping compared to both advanced climbers and individuals without climbing specific experience.

6.2.1 Methods

6.2.1.1 Participants

A total of 27 participants were recruited based on their self-reported prior climbing experience and ability (Draper, Dickson, et al., 2011). One group comprised participants (n=9, age = 21.5+1.6yrs) with a level equal to or lower than 5b on the French rating scale of difficulty (F-RSD) (corresponding to a lower grade or beginner level (Draper, Canalejo, et al., 2011)). A second group of nine individuals (age = 24.5+2.4yrs) were recruited on the basis of having a level between 7a-8a F-RSD corresponding to an intermediate level ability. The third group (n=9, age = 25.1+2.2yrs)) of participants comprised of professional firemen who were specialized ladder climbers. All participants provided informed consent and the study conducted with ethical approval by the participating institution's human ethics committee.

6.2.1.2 Experimental procedure and climbing route

Data were collected in a single session for each participant. Testing commenced with the participant being fitted with a safety harness and climbing specific shoes. After 10 minutes of climbing specific warm-up, participants completed a single, previewed and top-roped climb under on-sights conditions (first physical attempt). The route was graded at level 5b and was 10.4 m in height. The route was designed by an experienced setter and the difficulty level held constant at level 5b F-RSD and confirmed by consensus with two other qualified route setters. The route was specifically designed to induce meta-stable behaviour at each hold, by positioning three graspable edges at each hold: one horizontally aligned edge and two vertically aligned edges (refer to the supplementary material at the end of this chapter for the specific design route properties). Each participant was instructed to self-pace their ascent, with the task-goal of climbing in the most fluent manner possible, i.e., by minimizing jerky movement and prolonged pauses in body displacement. Prior to attempting to climb, each participant was allowed a three-minute period for the route preview (i.e. the individual looks at the route from the ground) (a number of pilot studies were carried out to establish the efficacy of route design and instructional constraints, see (Orth, Davids, & Seifert, 2013, 2014; Seifert, Orth, et al., 2014; Seifert, Orth, et al., 2013)). Following the trial, individuals were then asked to remain at the climbing wall for involvement in a follow up experiment.

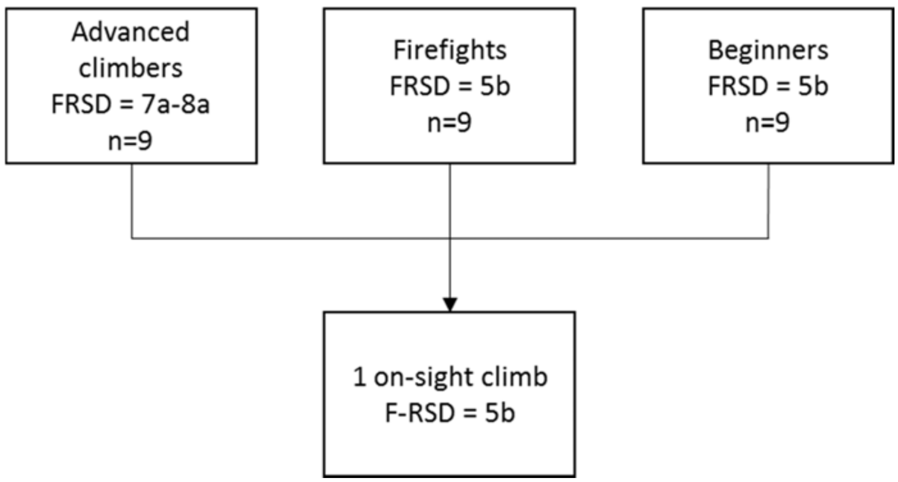

Figure 6-2. Experimental design Experiment 1.

6.2.1.3 Instrumentation

Participants were equipped with a luminous marker positioned on the harness at the body midline. Video footage of each ascent was captured at 60 fps with a frontal camera (Hero 3; effective pixels: 2592x1944) fixed 9.5m away from the climbing wall and at a distance of 5.4m from the ground. A calibration frame, 10.4m vertical x 3m horizontal and composed by 20 markers, was used to correct for distortion and calibrate the digitized trajectory from pixels to metres. Digitization was undertaken by an automatic tracking procedure that implemented a basic Kalman filter. Following this procedure any missing values in the time series were imputed using a Brownian bridge. These data were then subjected to low pass Butterworth filter.

6.2.1.4 Behavioural data

The third derivative of the 2D hip displacement referred to as the jerk coefficient of translation (JCT) was used to assess fluency or stability of the climbing performance (Ladha, Hammerla, Olivier, & Plötz, 2013; Pansiot, King, McIlwraith, Lo, & Yang, 2008; Seifert, Orth, et al., 2014) (see also Equation 4.1). Although a climber may intend to move fluently, their capacity to detect and adapt to informational properties specific to indoor climbing tasks can also be indexed by the number of exploration actions. According to Pijpers and colleagues, exploratory actions are primarily information gathering movements (Pijpers, Oudejans, Bakker, & Beek, 2006). Instances of exploratory actions specific to reachability were, therefore, coded when a hold was touched with a hand or the hand orientation was changed but not subsequently used to support body weight. Of major interest in this study was whether the prior experience of the climbers influenced the climber's tendency to choose one pattern of movement coordination over another. The edge orientation chosen at each hold was therefore collected where grasping orientations could correspond to either a horizontally orientated grasping action (where the knuckles of the hand run parallel to the ground plane, similar in orientation to grasping a ladder rung) or a vertically orientated grasping action (where the knuckles run perpendicular to the ground plane, similar in orientation to grasping the handle of a cup). These data were reduced to represent the ratio of vertical to horizontal actions that emerged with respect to the total number of actions used by each climber. Such that, when this value is equal to 1, 100% of the actions are overhand actions. When this value is equal to -1, 100% of the actions are vertical actions. When this value is equal to 0, 50% of the actions are overhand actions and 50% of the actions are vertical actions. The basic performance measure of the average time spent in 3-limb support and was also taken to determine whether participants were satisfying the basic task demand of achieving anchorage to wall (Sibella, Frosio, Schena, & Borghese, 2007). (Details pertaining to instrumentation and data reduction are provided in the Supplementary Material for this chapter and were discussed extensively in Chapter 4).

6.2.1.5 Statistical model and planned contrasts

A one-way ANOVA was used to evaluate the effect of group on the outcome variables of interest. Significance was set at p less than or equal to .05. Where Leven's test of the homogeneity of variance was significant, Welch's F was used with adjusted degrees of freedom reported and any subsequent comparisons were made assuming unequal variance. Statistical significance levels for main effects were corrected to account for the multi-comparisons (corrected alpha set to .0125). In the event of significant main effects, one-tailed linear contrasts were planned to determine whether the experimental groups (firemen and beginners) differed to the expert group in terms of the dependent variable, with a second contrast also undertaken to determine if a significant difference between the experimental groups was present. It was anticipated that whilst both experimental groups would demonstrate poorer performance in terms of route finding (jerk and exploration) the firemen would demonstrate better performance than the beginners on both of these variables. Additionally, it was anticipated that the experienced climbers would show a greater tendency to adopt vertically orientated grasping actions based on their prior experience. The firemen, on the other hand, were anticipated to show a stronger tendency to adopt horizontal grasping actions compared to the beginners and advanced climbers. Finally, because the route allowed climbers to take holds in a variety of ways, the capacity to achieve a baseline level of performance across all groups was anticipated.

6.2.2 Results with discussion

6.2.2.1 ANOVA effects with contrasts

There was a significant effect of experience on levels of jerk, $F(2,24) = 13.74$, $p < .0125$; total instances of exploratory actions, $F(2,12.283) = 19.946$, $p < .0125$; and grasp orientation tendency, $F(2,24) = 11.474$, $p < .0125$. There was, no significant effect for time spent in three limb support, $F(2,13.348) = 3.976$, $p > .0125$, suggesting that across all groups a base level of climbing performance was maintained (see Table 6.3 for a summary).

Table 6-3. Summary statistics of main effects and contrasts for Experiment 1.

Outcome variable	Main effect	Contrast 1[a]	Contrast 2[b]
Jerk of hip trajectory	$F(2,24) = 13.7$, $p < .01$*	$t(24) = 5.2$, $p < .05$*	$t(24) = .15$, $p > .05$
Time in 3 limb support	$F(2,13.3) = 4.0$, $p > .01$	N/A	N/A
Total exploratory actions	$F(2,12.2) = 20.0$, $p < .01$*	$t(15.9) = 5.8$, $p < .05$*	$t(12.8) = -.2$, $p > .05$
Hand orientation	$F(2,24) = 11.5$, $p < .01$*	$t(24) = 4.5$, $p < .05$*	$t(24) = 2.0$, $p < .05$*

*significant tests; **a**: intermediate vs. firefighters and beginners (1 tailed); **b**: firefighters vs. beginners (1 tailed).

The planned contrasts revealed that an absence of indoor climbing specific experience reduced climbing fluency, $t(24) = 5.2$, $p < .05$ (1 tailed), increased exploratory actions, $t(15.9) = 5.8$, $p < .05$, and led to a preference in overhand grasping actions, $t(24) = 4.5$, $p < .05$. Interestingly, fireman did not show better climbing fluency or less exploration compared to individuals with no general climbing experience as indexed by jerk, $t(24) = .15$, $p > .05$, and number of exploratory actions, $t(12.8) = -.18$, $p > .05$. Furthermore, contrasts did confirm that the fireman showed a significantly greater tendency to adopt overhand grasping actions during on-sight indoor climbing performance in comparison to the group with no general climbing experience, $t(24) = 2.0$, $p < .05$. Collectively, comparisons suggested that firemen, by virtue of their occupational specific experience in climbing (i.e. ladder climbing), have a stronger and spontaneous tendency to adopt specific behavioural actions, in this case overhand grasping. By contrast less experienced individuals show a small but significant tendency to adopt a greater variety of behavioural actions. These data are summarized below in Figure 6-3.

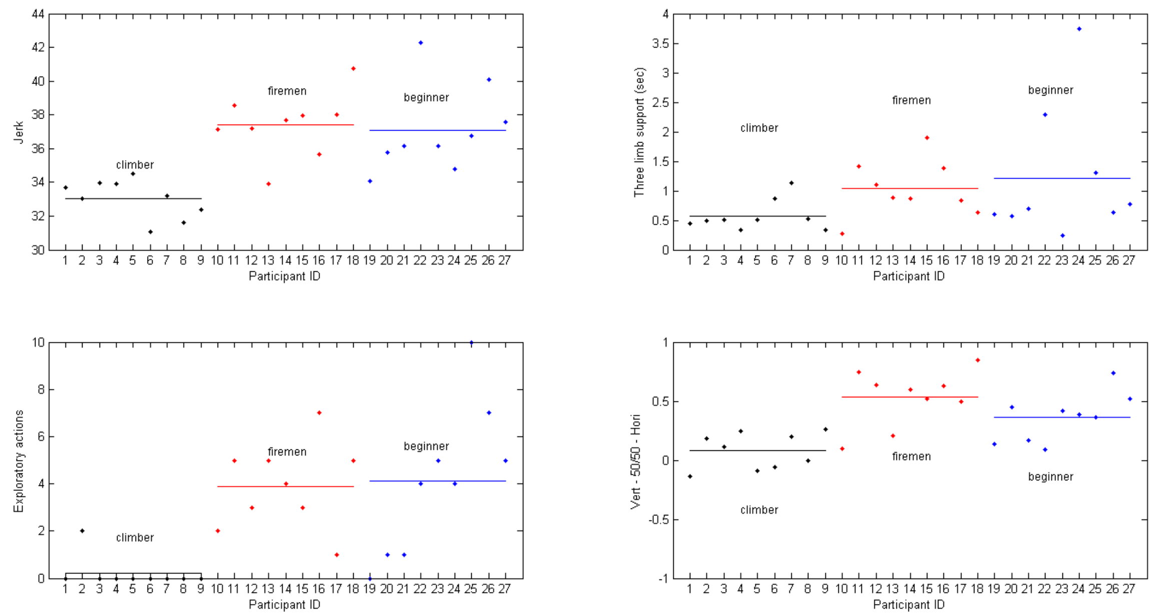

Figure 6-3. Summary data across the outcome variables in Experiment 1. All data points are the outcomes for each participant whilst the horizontal lines represent the group mean. **Vert** = Vertical grasping, **Hori** = Horizontal grasping, **sec** = seconds.

6.2.2.2 Key findings of Experiment 1

The purpose of this experiment was to test whether multi-articular performance in specific ecological is influenced by the intrinsic dynamics of individuals. It was anticipated that transfer of climbing fluency could be facilitated by experience in ladder climbing tasks. This study, however, did not provide support for general transfer underpinned adaptations that might be expected to accompany the occupation of firefighting. Jacobs and Michaels (2007) defined ecological constraints as supporting information-based adaptions to general forms of information shared across a range of contexts such as gravity. Hence it's interesting to consider why the firefighters could not transfer their experience of vertical climbing to the indoor climbing context. Indeed, the group of firefighters in this study could not be differentiated from a group beginner climbers in terms climbing skill, either in terms of fluency (jerk) or behavioural certainty (exploratory behaviour). These data would suggest that adapting to route properties reflects perceptual-motor adaptation to specific characteristics of the indoor climbing context such as route finding (Cordier, Mendès-France, Bolon, & Pailhous, 1993) or the different body positions or grasping orientations specific to the indoor climbing context (Boschker et al., 2002). Although, another possible explanation is that climbing fluency was supported by strength specific adaptation in the finger flexors in the advanced climbers (which support friction at the finger-tips (Vigouroux & Quaine, 2006)), the holds were designed to be graspable with the entire hand. Hence, this suggests that the beginners (fire-fighters included) demonstrated a lower fluency due to information-based reasons.

There was support shown, however, for the transfer of a behavioural tendency, with firefighters showing a greater likelihood to grasp hand holds with an over hand grip in comparison to both the experienced climbers and beginners. It was anticipated that these two groups would show a spontaneous tendency to use overhand grasping. A reason why the firefighters showed a stronger tendency toward overhand grasping is therefore possibly due to their occupational experience, often requiring them to climb ladders wearing and carrying heavy equipment. However, in contrast, individuals with less climbing experience either in terms of ladder climbing or indoor climbing used a greater variety of grasp orientations, albeit, to a less extent than experienced climbers. In tasks that require fine motor control, similar results have previously been shown. For example, Semmlet and Nordsrom (1998) compared strength athletes to both a skilled musician group and a control (no specific training) group in terms of finger flexor motor unit synchrony. It was found finger flexor motor unit synchrony was significantly weaker in highly trained musicians, compared to both strength athletes and a control group. It was further shown that the strength trained group showed the highest motor unit synchrony. These findings suggesting that chronic skill specific use of the fingers in musicians induced adaptations that reduced motor unit synchrony (Carroll, Riek, & Carson, 2001). And furthermore, individuals without strength training also showed significantly less synchrony than the strength trained group. These findings suggest that strength-specific adaptations (e.g., muscle fibre growth, improvements in activation efficiency) can reduce the ability to exhibit more variability in contexts requiring refined movement control (Baratta et al., 1988; Carroll, Abernethy, Logan, Barber, & McEniery, 1998; Semmler & Nordstrom, 1998).

Future research should, however, confirm whether the firemen do not benefit from a general form of transfer. Whilst they did not show a transfer of skill (i.e. improved performance due to experience), it is possible that they would show a transfer of learning (improved rate of learning) (Issurin, 2013). An additional limitation in the above study is that it is unclear in what way different body-wall orientations can influence climbing performance. For instance it is possible to take a hold with a vertical-edge and still remain facing the wall. Indeed, the findings of Experiment 1 raise the concern that the way a hold is taken does not appear to relate to fluency.

6.3 Experiment 2: Can beginners use the same coordination patterns as experienced climbers?

The findings from Experiment 1 provided evidence that intrinsic dynamics influence the coordination patterns that are spontaneously adopted in inexperienced indoor wall climbers under on-sight conditions. A key finding of Experiment 1 was that whilst, there were different types of grasping actions used by the less experienced individuals and firefighters, these two groups of individuals showed no significant difference in climbing fluency. This suggested that the hand orientations adopted were not driving the performance outcome, reflecting instead, movement system degeneracy (capacity to achieve the same outcomes with different behaviours).

The main uncertainty, therefore, was that whilst in the first experiment intrinsic dynamics was shown to influence emergent behavioural tendencies, it was unclear how the intrinsic dynamics of climbers influenced their climbing fluency. Rather than climbing fluency being driven at the level of the limbs, an experiment was conceived to determine what parameters climbers need to adapt in order to maintain fluency and that could determine at what level analysis coordination differences would be apparent based on experience. It was assumed that different coordination patterns require learning in climbing (i.e. side-wall climbing) and that experienced climbers could successfully adapt movement parameters (spatial complexity and temporal fluidity) to these for achieving smooth climbing. For these reasons a second experiment was conducted involving a scanning procedure designed to observe individuals with differing levels of experience climb using different body-wall orientations (face- and side-wall configurations). The purpose of a scanning procedure is to assess an individual's multi-stability. For example, prior to learning a new skill, a scanning procedure can uncover the pre-existing stable and unstable coordination tendencies when performing in a given context and then determine how the landscape is affected by practice under a specific arrangement of constraints (Kostrubiec et al., 2012; Zanone & Kelso, 1992). The approach involves scaling a parameter such as a required body position and observing effects on overall movement coordination. The result of this process is to uncover what control variables individuals may use to maintain the stability of a given performance pattern.

In the following experiment, two groups were formed. One group, composed of individuals with no indoor climbing specific experience and the second group composed of experienced indoor climbers. Groups were then required to climb the same route as in Experiment 1, but under three separate conditions. One condition was the reference condition where individuals were asked climb with no specific instructions imposed (self-preferred). One condition required climbing as much as possible with the front of their body facing the wall and a final condition requiring climbing with the side of their body facing the wall for as much as possible during climbing. It was anticipated that the ability to maintain a given body-wall relationship would be dependent on the individuals intrinsic dynamics. Beginners, being less capable of climbing in the side-wall attractor space compared to the experts, but equally capable in climbing in the front-wall attractor space. That is, the experienced climbers would show multi-stability in the body-wall attractor space, whereas individuals with no indoor climbing specific experience would show mono-stability.

6.3.1 Methods

6.3.1.1 Participants

Two groups of participants were recruited into the study. Specifically ten advanced climbers (age = 23.5+2.2yrs) and 15 inexperienced climbers (age = 22.5+2.3yrs).Eligibility criteria require that experienced climbers have an advanced level of climbing ability (corresponding to greater than 7a on the French rating scale), and the inexperienced climbers at no greater than level 5b.

6.3.1.2 Experimental procedure and climbing route design

Data were collected on a single day for each participant which involved, upon arrival, being equipped with a harness and climbing shoes. A red light was fixed to the harness over the sacroiliac joint (although climbing shoes were depended on the individual, the same harness was used across all participants). An inertial measurement unit (IMU) was then fixed at the hip and on the wall (see Supplementary Material for this chapter for specific placement details). Participants then completed a climbing-specific warm up. They then completed three, top-roped climbs under different instructional conditions (the order of which were counterbalanced using a Quasi Latin Square design). Between each climb, a seated 5-minute rest was enforced and the individual given more time if desired before commencing any following trials.

Across all conditions individuals were requested to climb to the top fluently, without prolonged pauses and avoid falling. Finally, prior to commencing the experiment, because the purpose of the scanning procedure was to assess the movement coordination, individuals were given a single trial of physical practice prior to assessment to reduce the route finding problem. Furthermore, in order to emphasis the motor coordination element of the testing, the individuals were shown the location of holds prior to testing using a laser pointer (refer to the supplementary material at the end of this chapter for the specific design route properties).

Prior to undertaking each test specific instructions were given. For the reference condition individuals were asked climb to the top fluently, without prolonged pauses and avoid falling (self-preferred). In the face-wall condition, individuals were instructed to climb as much as possible with the front of their body facing the wall and as fluently as possible, without prolonged pauses and avoid falling. In the side-wall condition instructions were to climb as much as possible with either side of the body facing the wall. It was anticipated that the ability to maintain a given body-wall relationship would be dependent on the individuals intrinsic dynamics.

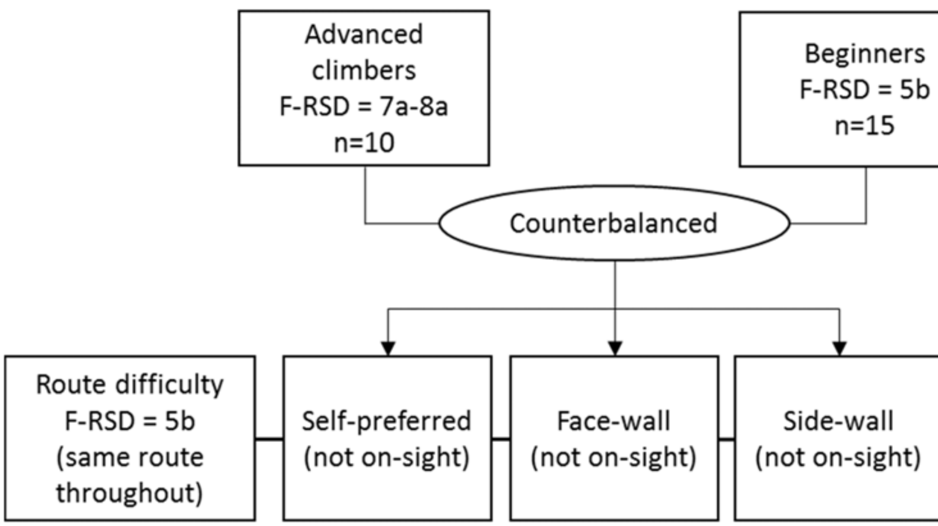

Figure 6-4. Experimental design Experiment 2.

6.3.1.3 Instrumentation

Data collection was via video filming and image processing and extraction of raw orientation signals transmitted from IMUs. The primary variables of interest with regard to video analysis were the jerk coefficient of translation (JCT, equation 4.1), geometric index of entropy (GIE, see equation 4.2), and immobility to mobility ratio (IMR, equation 4.3). Instrumentation approaches are detailed in the

Supplementary Material for this chapter. The variable of interest with regard to the IMUs was the angle formed between the trunk and the wall in the transverse plane (refer to Figure 6.5). (Instrumentation approaches for the IMU are detailed in the Supplementary Material for this chapter.)

Although determining the trunk-wall angle was a novel method for assessing coordination in climbing, similar methods have been applied at the limb level for understanding stable and unstable patterns of inter-limb coordination in climbing tasks (see (Seifert, Coeurjolly, Hérault, Wattebled, & Davids, 2013)) and a rational for assessing angular relationships between trunk and thoracic rotations around the longitudinal previously established (Amblard, Assaiante, Lekhel, & Marchand, 1994; Temprado, Della-Grasta, Farrell, & Laurent, 1997)).

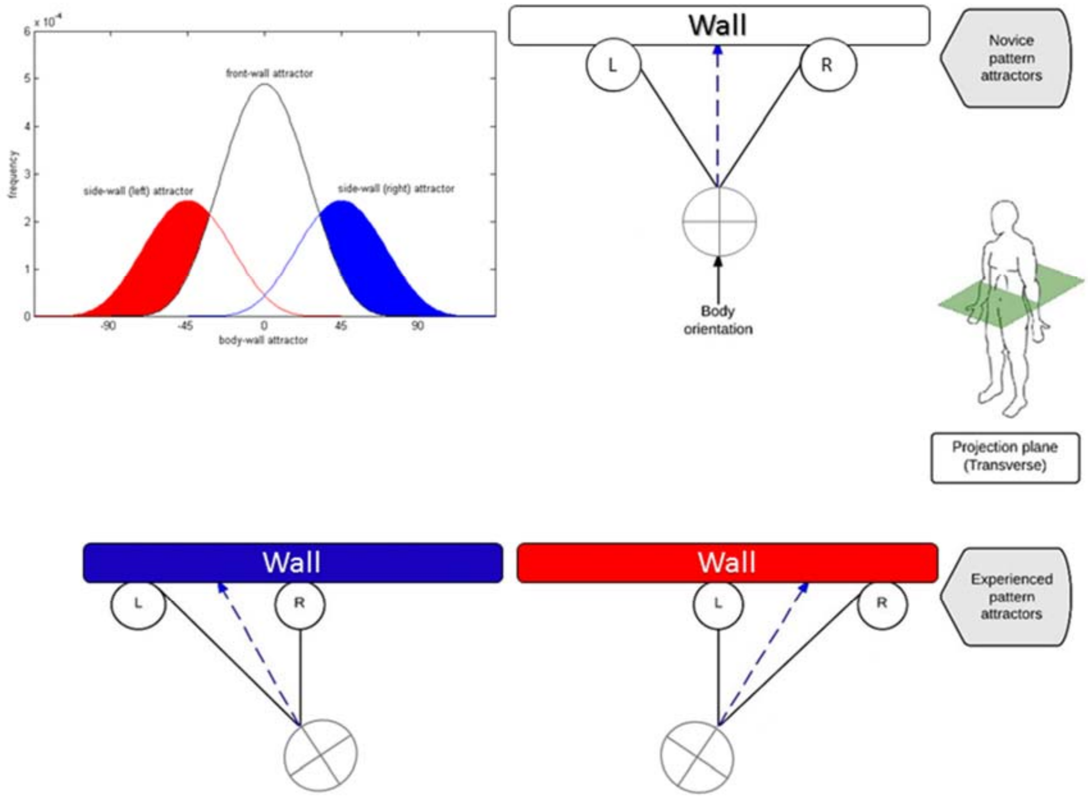

Figure 6-5. Hypothetical depiction of the attractor space in terms of angular position between the body and the climbing wall with respect to the transverse plane. **L**= left hand, **R** = right hand.

6.3.2 Results with discussion

6.3.2.1 Descriptives

By the conclusion of the experiments, five of the beginner climbers fell during one or more of the conditions. These individuals were, therefore, grouped separately during analysis since their ability level was not matched to the route. Indeed, during descriptive assessment it was clear that their inclusion in the less experienced group would confound the results. For example, in some cases a number of climbers who fell showed lower levels of jerk compared to their more experienced counterparts. Although JCT, GIE and IMR are dimensionless, this outcome is most likely because they fell early in the route without any substantive searching or route finding behaviour. Nonetheless, interesting points were raised in considering the data of fallers alongside the individuals who successfully completed the route and for this reason their outcome results are included for discussion but their data were excluded from statistical analysis. The descriptive raw outcome data, including means and standard deviations on JCT, GIE, IMR and a density histogram of body-wall angle grouped by way of advanced climbers, beginner climbers and those who fell can be seen in Figure 6.6. Specifically, the density histogram is normalised so that area under the curve (as represented by the heights of the bars) is equal to 1. Noting also that the bin widths were determined using Sturges' Rule (Martinez, Martinez, & Solka, 2010). The purpose of this procedure is to get a closer estimate of the distribution (for example an arbitrary number can reveal spurious peaks, giving the impression of multiple modes).

Broadly, the descriptive data shown in Figure 6.6 suggest that advanced climbers show better smoothness in trajectory, entropy and spend less time immobile. It was somewhat surprising, however, to observe no major difference in the body-wall angle between each of the three groups. The only difference in the nature of the distributions was that the intermediate climbers were able to maintain a more narrow range when climbing face-on to the wall and no major indication that a side-wall orientation was unavailable to beginner climbers or climbers unable to complete the route. However, when conducting the experiment it was clear that in some cases, the beginner climbers, were capable of taking the side-wall position primarily during periods of immobility. A major concern was that when the beginners were mobile they were adopting the face-wall position and resting in the side-wall position in order to the follow the instructions as best they could. Indeed, the immobility data was shown to be higher in the beginners overall (refer to Figure 6.6) and the experienced climbers also showed a clearly significant reduced the time spent immobile when requested to climb side-on to the wall (Figure 6.6, third panel row). This is contrasted with the beginner climbers who show no indication of a condition effect in terms of climbing immobility.

These concerns are analysed in detail below, with the key result being that whilst beginners could readily adopt a stationary side-wall position, their performance suffers. Furthermore, in cases where individuals fall, these individuals appear to be unable to use the side-wall position whilst mobile.

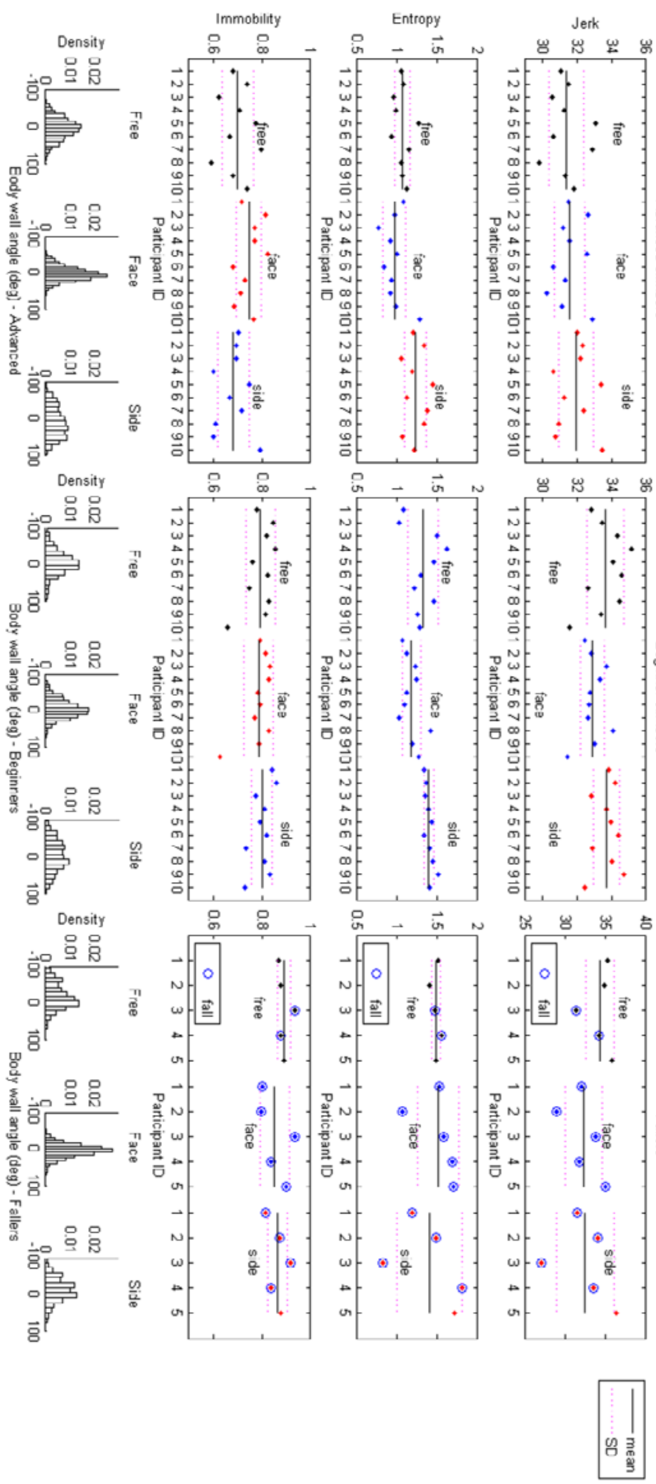

Figure 6-6. Summary of the variables of interest in Experiment 2. **ID** = identification. **SD** = standard deviation. Note the difference in scale on jerk and entropy for the faller group compared to the advanced and beginner groups which was increased to ensure visualisation of the data.

6.3.2.2 MANOVA with follow-up

The initial multivariate ANOVA, using Pillai's trace (V), showed there was a significant effect for experience on smoothness, entropy and immobility for the free (V = .526, F(3, 54) = 5.914, p = .006), face (V = .516, F(3, 54) = 5.688, p = .008), and side-wall (V = .631, F(3, 54) = 9.114, p < .001), climbing conditions. These results suggested that climbing experience was charactered by each variable in combination. In follow-up the mixed design ANOVA were carried out separately on JCT, GIE and IMR outcomes on the independent levels (experience: advanced climbers verse beginners) and dependent levels (instruction: free, face-wall, and side-wall conditions). Levene's test was then used to assess the equality of variance between groups on each of the outcome variables with entropy under the free climbing and side-wall conditions revealing significant violations (F(2,18) = 6.03, p = .024, F(2,18) = 8.643, p = .009). For these cases an independent t-test assuming unequal variance were carried out using an adjustment in the degrees of freedom and in each case a group effect was still found for both entropy in the free- (t(1, 12.832) = 3.712, p = .002) and side-wall (t(1,12.159) = 3.538, p = .004) conditions. Tests for homogeneity were then carried out for the dependent levels, where corrections for violation of sphericity using the Greenhouse-Geisser correction are reported in the adjusted degrees of freedom (specifically, Mauchly's test showed up significant for the JCT outcome; $X^2(2) = 9.378$, p = .01). In cases of significant main effects, focused contrasts were then followed up to understand the main effects. Significant effects are reported at equal to and less than 0.05.

As anticipated, there was a main effect for experienced in JCT, F (1, 18) = 25.655, p < .001, with advanced climbers showing smoother climbing trajectories (lower jerk) overall. On the other hand, a near, but statistically non-significant main effect for condition on the JCT outcome was shown, F =3 .511(1.4, 25.28), p =.06. Similarly a near statistically significant interaction effect of condition by group was also shown for JCT, F = 3.561(1.4, 25.28), p=.06. In fully considering the data, the near significant effects were apparently driven by the effect of experience when going from free climbing to climbing under instruction to remain face to the wall climbing and, further when going from face to the wall to side-wall climbing. Specifically, experienced climbers showed no substantial change in free vs face ($t(9) = -1.396$, $p = .19$), and face verse side ($t(9) = -1.266$, $p = .19$), suggesting that the advanced climbers adapted effectively to each instructional condition to maintain performance. On the other hand, the beginners improved smoothness when climbing face to the wall compared to the free condition ($t(9) = 3.062$, $p = .02$, 2-tailed), whereas smoothness decreased when climbing side-on to the wall compared to the face-wall condition ($t(9) = -3.033$, $p = .02$, 2-tailed). These statistics are however tempered by the lack of significance in the repeated ANOVA.

With regards to both entropy and immobility, tests were significant for the main effect of experience, with advanced climbers showing overall lower entropy ($F(1, 18) = 22.378$, $p < .001$) and immobility ($F(1, 18) = 14.798$, $p < .001$), as expected. Outcomes on entropy showed a significant main effect for condition ($F(2, 36) = 25.302$, $p < .001$), and no significant interactions between condition and experience, ($F(2, 36) = 1.265$, $p = .29$). On the other hand, immobility, showed no significant effect for condition ($F(1, 18) = 2.027$, $p = .15$), but revealed a significant interaction effect for the condition by group test ($F(2, 36) = 5.77$, $p = .01$). Focussed contrasts were thus undertaken to disambiguate these results. For entropy, contrasts confirmed that for both groups, the level of entropy reduced significantly under the face-wall condition compared to the free climbing condition ($F(1,18) = 13.813$, $p = .002$). Entropy also significantly increased in the side-wall condition compared to the face-wall condition ($F(1,18) = 56.781$, $p < .001$), indicating that it was these changes driving the main effect for entropy.

For immobility, contrasts showed that in going from the free climbing condition to the face-wall condition the outcome of immobility was dependent on the experience level of the individual

(F(1,18) = 8.598, p = .01). Whilst the experienced climbers significantly increased their immobility time when climbing face-on to the wall, the beginner climbers did not significantly change their time spent immobile, who no significant differences between the free- and face-wall conditions. Furthermore, when going from the face-wall condition to the side-wall climbing condition, the outcome of immobility was also dependent on the experience level of the individual (F(1,18) = 10.334, p = .01). In this case, the interaction effect was driven by the fact that whilst the beginner climbers did not modify their immobility time in the side-wall condition compared to the face-wall condition, the experienced climbers significantly reduced their immobility time when under the side-wall instructional constraint. The relationships between immobility, entropy and jerk are visualised in Figure 6.7.

The data in Figure 6.7 shows that for advanced climbers, in order to maintain smoothness under different instructions, both spatial and temporal features of movement are adapted. The key findings presented are that for advanced climbers, when requested to climb side on to the wall, they tended to increase climbing mobility in order to maintain smoothness or at least to follow the instructional constraints of the experimenter. Additionally, a clear relationship between reduced entropy, lower immobility and lower jerk are shown. Finally, the impact of falling on performance outcomes is also highlighted with individuals who fell recording both the best and worst jerk outcomes showing that the amount of vertical distance achieved can confound interpreting these types of data.

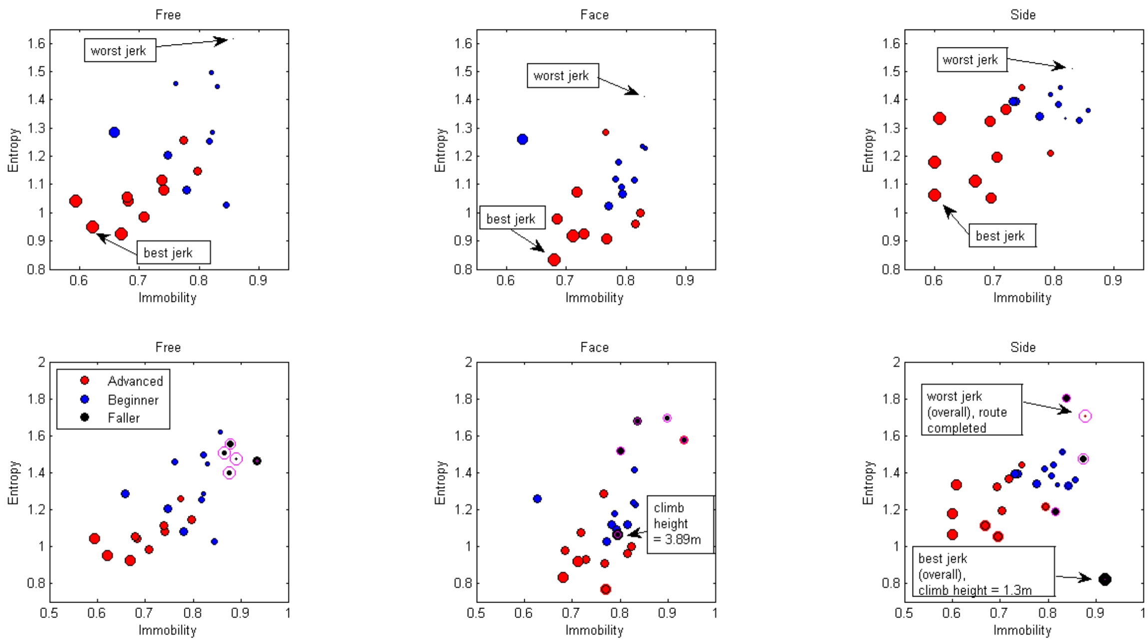

Figure 6-7. The relationship between climbing smoothness, entropy and immobility as a function of climbing modality.

Specifically in Figure 6.7, red filled markers are advanced climbers, blue filled markers are beginner climbers and black filled markers and individuals who fell on at least one of the routes during the experiment. Note that the diameter of each marker is scaled to the outcome measure of jerk which was normalised so that the lowest (smoothest) jerk value is equal to 100 and highest jerk value (least smooth) is equal to 1, hence the bigger the marker the better the smoothness. In the top row of graphs (not containing the fallers) the normalisation on smoothness maintains the respective distances of the original data on a condition-wise basis. Whereas, in the bottom row of graphs (includes the fallers) the normalised values are with respect to all individuals across the entire experiment. Because falls might influence measures based on the distance covered, a second circle scaled to the vertical distance climbed was placed around the faller group data (bottom panel). The smaller this circle, the less height the individual achieved, the larger the circle the greater the height achieved.

Collectively, these findings indicate that climbing smoothness was dependent on the level of entropy and immobility in combination. In disambiguating the underpinning causes of each effect, it was shown that experienced climbers show different adaptations in the outcome variables depending on the nature of the coordination pattern required. Specifically, in order to maintain smoothness when using the different body-wall relationships, advanced climbers adapted both behavioural complexity and their degree of dynamic state in combination and in significantly different respects to the beginners. Intermediate climbers maintained smoothness, when climbing face to the wall, by concomitantly reducing behavioural complexity and increasing the time spent immobile. Whereas on the other hand, when required to climb side to the wall, the advanced climbers concomitantly increased behavioural complexity and reduced immobility. In the beginners however, whilst they could reduce behavioural complexity in the face-wall condition, they did not co-adapt their immobility (although smoothness did show a tendency to improve). Similarly in the side-wall condition whilst entropy increased, there was no significant change in immobility and smoothness showed a tendency to worsen. These data suggesting that, in order to use side-wall movement patterns smoothly, adaptation in climbing state needed to be concomitant.

6.3.2.3 Qualitative follow-up

An in depth, qualitative analysis of the distribution of the hip-wall angle was undertaken to consider whether it was dependent on either the height participants climbed and/or the state of mobility of the participants. In the first step, the hip-wall angle was separated into two time series, one where the climber was detected as mobile (moving faster than 25cm/sec, refer to Chapter 5 for details) and the other where each climber was detected as immobile (moving slower than 25cm/sec). The separate time series were then plotted as a normalised density histograms for each group (advanced, beginners and fallers) and for each instructional condition (free, face, side).

The findings, shown in Figure 6.8, indicate that the beginners who successfully climbed the route (graphs with grey background), the state space used during mobile climbing was very similar to the advanced climbers (graphs with white background in Figure 6.8). This suggests that the beginners may be considered in the control stage of learning (Chow, Davids, Button, & Rein, 2008), where the coordination state is available, but the individuals require more extensive practice to improve its stability on account of their worse jerk. On the other hand, the data showed that for individuals who fell, they were unable use the side-wall position in the dynamic state, suggesting they are in the coordination stage, still needing to find the side-wall coordination pattern (see the right side panels coloured in black in Figure 6.8). The fallers did however, show the ability to explore the side-on state space whilst immobile (see the left side panels coloured in black in Figure 6.8).

Of additional concern was that the height achieved could influence the body-wall angle achieved. This led to considering how the coordination pattern used may have also been related the amount of displacement achieved. It was possible that, whilst the beginner climbers may have been able to use the side-wall orientation early, as they achieved greater vertical displacement they may have been unable to continue to use the requested mode of coordination due to emerging constraints such as fatigue or anxiety over falling (Pijpers et al., 2006). For this reason, the time series data were split into two halves. Specifically, the first and second of half of each climb trial of the body-wall angle were analysed (and accordingly to their respective dynamic and static states). The main finding, shown in Figure 6.8, was that there was no effect of climb distance on the beginner climbers' ability to use the side-wall movement pattern when mobile. Instead the data only reinforced that the climbers who fell were unable to use the side-wall body position.

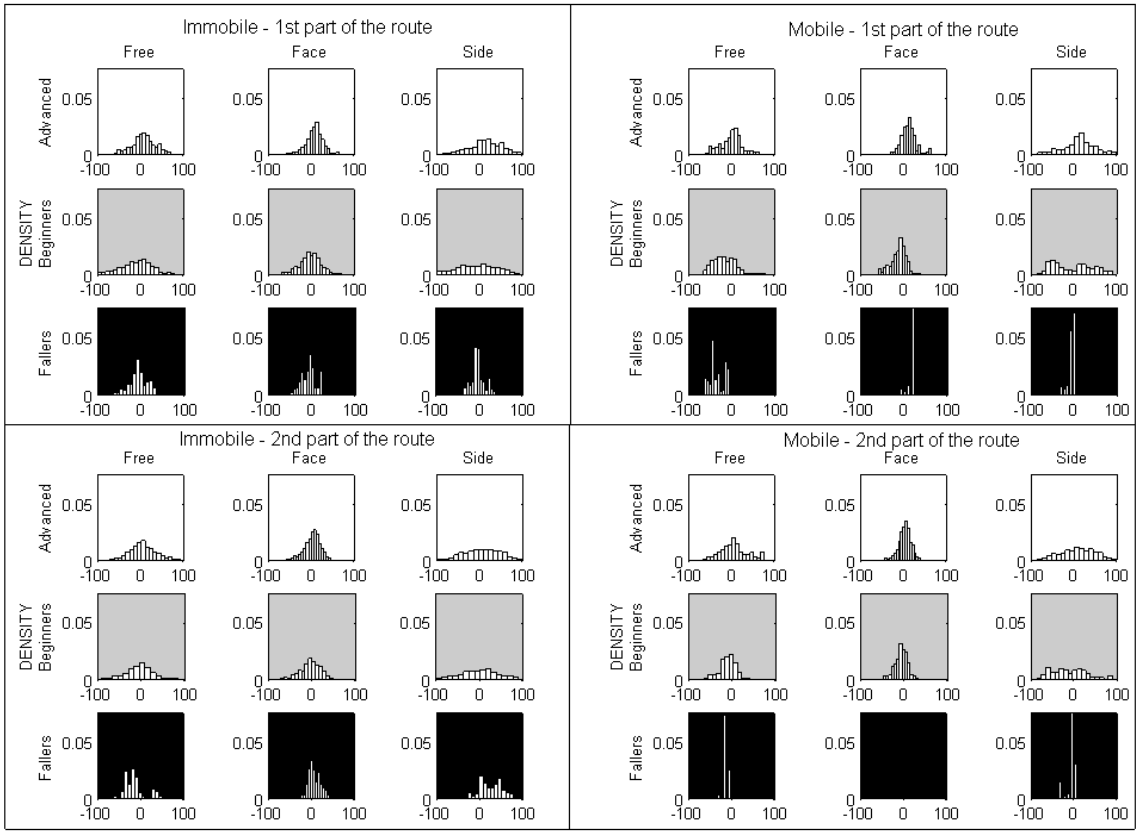

Figure 6-8. The relationship between first and second half of the time spent climbing on hip-wall angular relationship.

6.3.2.4 Key findings Experiment 2

The purpose of the second experiment was to determine whether certain body-wall relationships require learning in order to use effectively. It was anticipated that a scanning procedure would reveal a candidate order parameter and key control parameters that climbers regulate for achieving fluency. A multivariate relationship was shown between immobility and trajectory complexity that climbers regulated in combination for maintaining smooth climbing displacement. Whilst advanced climbers are able to effectively modify mobility with more complex behaviour (climbing side on the wall), beginners are unable to do so, their smoothness suffering as a consequence. In this respect, although the beginners could use the side-wall pattern, they were unable to use the pattern effectively. The notion of effectiveness exemplifying in how the beginners smoothness showed a tendency to benefit from being instructed to climb with a face-wall orientation.

Another key finding in this study was that beginners can functionally adapt the side-wall coordination pattern, even under states of mobility and after prolonged climbing. Furthermore, individuals who fell were clearly were unable to use the side-wall position in a mobile state, suggesting that the side-wall coordination pattern that requires learning is nested with the state of mobility. These data broadly lend support to characterising climbing skill using spatial and temporal measures in combination, that certain body-wall relationships can require learning, and that scanning procedures may be an effective tool for understanding the impact of intervention on behavioural flexibility in complex multi-articular tasks.

6.4 Experiment 3: Learning dynamics and the transfer to skill in a physical activity task

When faced with a new learning context, individuals can adapt existing patterns of coordination as a platform to find new and better performance solutions (Newell, 1991, 1996; Teulier & Delignières, 2007). After determining appropriate coordination patterns, individuals further refine ways of adapting these (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003). For example, Nourrit et al., (2003) observed five beginners over 39 trials of practice revealing at the individual level of analysis examples of: linear improvement; transitional; and, complete lack of improvement. Different rates of learning have also been associated with the discovery of new movement patterns in complex multi-articular tasks where in some cases, even after extensive practice beginners can fail to locate new movement patterns. In this respect, Delignières et al. (1998) found that beginners and experienced gymnasts differed significantly in up-side-down swinging on parallel bars, both in terms of relative phase and frequency ratio between upward and vertical oscillations of the COM. Whilst beginners spontaneously adopted a coordination mode characterized with a 1:1 frequency ratio and in-phase pattern, the experienced gymnasts used a 2:1 frequency ratio and 90/270° phase offset, allowing them to achieve significantly larger swing amplitudes compared to the beginners. The beginners were then given 80 practice trials over eight sessions with the goal of improving swing amplitude. It was found that no change in the coordination solution emerged in the group of beginners, although improvements in movement amplitude were recorded (for a similar outcome despite extensive practice see (Komar et al., 2014)). These data suggest that a number of factors can influence the discovery of new coordination patterns in complex multi-articular tasks and include: the relationship between the individual's intrinsic dynamics and the practice constraints (Delignières et al., 1998); the time provided to practice (Nourrit et al., 2003); and, to what extent constraints facilitate the discovery of the coordination pattern (Boschker & Bakker, 2002; Komar et al., 2014).

Indeed, simple task models have shown that prior stable patterns of movement coordination, can shape learning (Kelso, 1995; Yamanishi, Kawato, & Suzuki, 1980) acting as a point of potential resistance or inhibition to actions more functional to new performance constraints (Caillou, Nourrit, Deschamps, Lauriot, & Delignieres, 2002; Kostrubiec, Tallet, & Zanone, 2006; Kostrubiec et al., 2012; Tallet, Kostrubiec, & Zanone, 2008). For example, Kostrubiec et al. (2012), showed learning new phase relationships in a finger waggling task, could be characterised in two different respects that depended on the intrinsic dynamics of the individual prior to learning. In one respect, learning was characterised as a shift of a stable coordinative state in the direction of the to-be-learned pattern involving a linear like evolution of the initial coordination dynamics. In these individuals, the intrinsic dynamics were characterised prior to leaning as exhibiting three stable regions of performance. On the other hand, some individuals were shown to exhibit non-linear abrupt transition in the nature of the coordination solution during practice, suggesting the emergence of a new pattern or skill through transition. In these individuals, the intrinsic dynamics were bi-stable prior to learning. Hence, according to Kostrubiec et al. (2012) the route of learning is dependent on the initial intrinsic dynamics of the individual and how much the coordination requirements for improving performance compete or cooperate with the individuals existing intrinsic dynamics.

Similarly in complex multi-articular skills the acquisition of new behaviours may not bear a linear relationship to the time spent practicing, showing sudden transitions between different patterns or regression back to 'old' patterns during learning (Chow, Davids, Button, & Koh, 2008; Teulier & Delignières, 2007). This can be, for example, because systems important for performance can develop at different rates (e.g., strength, neural adaptation, confidence, (Thelen, 1995)) or due to false minima in the movement coordination landscape (Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009), where individuals get stuck in a non-optimal solution because the learning constraints lack essential variability. Intervention induced variability during practice can for example allow individuals to more extensively explore the possible states of coordination, preventing them from becoming 'stuck' in solutions that may not be optimal (Huet et al., 2011; Liu et al., 2012; Schöllhorn et al., 2009). Indeed, even experienced individuals naturally exhibit ongoing exploration of different movement patterns when it is supports goal achievement (Hristovski, Davids, Araújo, & Button, 2006; Pinder et al., 2012).

However, the relationship between exploration during learning and later performance outcomes is not entirely clear. For example, in order to consider the effect of more or less exploration during practice on skill outcomes, Lee et al. (2014), undertook an intervention study comparing a *non-linear pedagogical approach* to a *prescriptive approach*. Individuals underwent 4 weeks of practice involving two 15 minute sessions a week consisting of 80 trials of tennis ball hitting. The non-linear group experienced a broad range of constraints during practice including the manipulation of net height, target area, court size, and rules to achieve specific task goals. In the linear group, instructions involved having individuals learn a predefined movement pattern through the use of prescriptive cues and repetitive drills, which according to Lee et al. (2014) left negligible opportunity for exploration. Instructions for example included prescribing how each phase of the tennis striking technique should be performed. In a follow-up retention test, it was found that the linear group showed better performance. However, the analysis of each individual's kinematics was also undertaken and revealed a greater number of movement patterns were present in the post-test sessions in the non-linear group. This suggests that the greater exploration supported during practice helped to develop degeneracy in the learners. Unfortunately in this study, no transfer test was undertaken to evaluate whether the enhanced exploration led to more effective transfer of skill. Additionally, it is unclear whether individuals learnt any new skills, because, the prior ability of the participants to adapt various patterns of coordination were not tested.

Therefore, the aim of Experiment 3 was to evaluate the role of a learning design that facilitated exploration during skills practice and test whether extended practice under such constraints can support the acquisition and transfer of skill. Assuming that the beginners can benefit by practicing under conditions that represent meta-stability (as shown in Chapter 5, Study 1), the major aims of this experiment were to observe the emergence of new coordinated behaviours relative to the initial learners skills; evaluate potential relationships to exploratory behaviour, and; to determine whether such practice constraints can support performance similar to individuals who have naturally acquired their skill through undertaking transfer tests.

6.4.1 Methods

6.4.1.1 Participants

Ten individuals without prior experience of rock climbing were recruited. Inclusion criteria required that participants be within the healthy BMI range (<25) and have an arm span of no less than 140 cm (for details see Supplementary Data).

6.4.1.2 Experimental procedure and climbing route design

The learning study involved two pre- post-test sessions (four in total), and 14 learning sessions in total (two learning sessions per week over a seven-week period that required at each session three trials of practice and, therefore, 42 trials of practice overall). The volume of practice was chosen because it corresponds roughly to a normal term of a beginner level climbing course. Pre-testing was carried out one-week in advance prior to commencing the learning sessions and post-testing carried out one week after the final learning session (refer to the supplementary material for an overview of the study design).

During each pre- and post-test session participants completed three top-roped climbs. The first pre- and post-test sessions (session 1 and session 17) involved climbing three separate routes, the learning route, and two different transfer routes. The second pre- and post-test sessions (session 2 and session 18) required participants undergo the scanning procedure as detailed above in Experiment 2. Between each climb, a seated 5-minute rest was enforced. The order for each climb during the testing sessions was also counterbalanced to control for possible order of treatment effects. In all cases, the general instructions given to participants was to climb the route as fluently as possible, minimising jerky movement, taking an efficient path through the route and minimising prolonged pauses. Globally all routes were designed at 5b F-RSD.

6.4.1.2.1 Scanning procedure

In using the same procedures as outlined in Experiment 2 above, the scanning procedure required participants to climb the learning route under three different instructional constraints either: using their self-preferred manner; whilst maintaining a face-wall orientation; or whilst maintaining the side-wall orientation as much as possible. The same route as used in Experiment 2 was used in this experiment (refer to the supplementary material at the end of this chapter for the specific design route properties).

6.4.1.2.2 Transfer route 1: Holds in unique positions

The first transfer route was designed specifically to challenge the route finding skill of the participants by positioning holds in different locations and with varying complexity. The aim of this design was to require the participants to adapt different ways of passing between holds compared to the learning route (refer to the supplementary material at the end of this chapter for the specific design route properties).

6.4.1.2.3 Transfer route 2: Holds with smaller graspable surfaces

The second transfer route was designed using holds at the same locations as the learning route but with smaller and less visually obvious grasping edges. The aim of this design was to challenge the participants' ability to perceive the graspability of the holds (refer to the supplementary material at the end of this chapter for the specific design route properties).

6.4.1.2.4 Learning sessions: Route and procedures

At the beginning of each learning session feedback of climbing fluency was provided regarding the previous learning session (specifically individuals were given three values, their jerk, entropy and immobility and adopted climbing trajectory for each trail, see Figure 6.9 for an example, these images were both emailed to the participants within a 48h period after each learning session and shown again at the beginning of each learning session). During each learning session participants completed three previewed, top-roped climbs. Between each climb, a seated 5-minute rest was enforced. The same route as used in Experiment 2 was used for the learning route in this experiment (refer to the supplementary material at the end of this chapter for the specific design route properties).

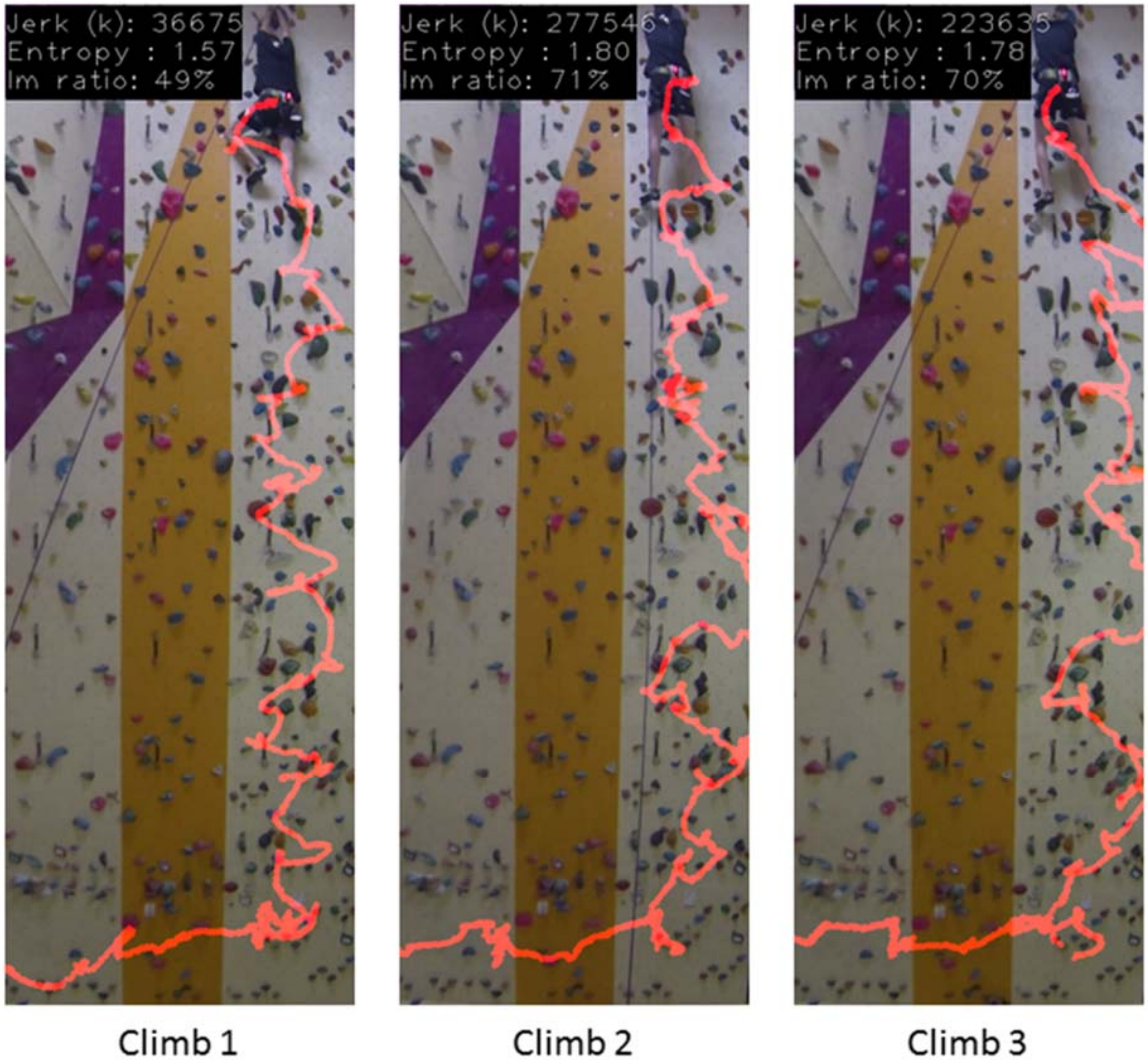

Figure 6-9. Example of the feedback given to learners at the end of each practice session.

6.4.1.3 Instrumentation

Data collection were via video filming and image processing and extraction of raw orientation and acceleration signals transmitted from worn sensor units (see the Supplementary Material at the end for details). In this experiment, IMUs were used to determine the body-wall angle at the hip and also to measure the number of exploratory actions at the limbs throughout practice. For this reason in addition to IMUs being placed at the harness and wall, IMUs were also placed at the wrists and feet of the climbers (see the Supplementary Material at the end for details).

6.4.1.4 Behavioural data

The primary variables of interest with regard to video analysis were GIE, JCT and IMR. These were used to address the individual's performance, the dynamics of performance during learning and the capacity for the participants to transfer their skills to different route designs (refer to Chapter 4 for an extensive review on the choice of these variables and the outcomes from Experiment 2 above for their utility as a marker of performance). As shown in Experiment 2, because the potential that new skills might emerge during practice observable in the body-wall relationship, was used in a qualitative approach to assessing the movement coordination during the scanning tests and throughout learning. The exploratory behaviour of the learners during practice and transfer was also of significant interest in this study and were collected using the IMUs.

6.4.2 Results with discussion

This section addresses whether: a) meta-stable practice constraints can support performance similar to individuals who have naturally acquired their skill based on the outcomes of the transfer tests and scanning procedure; b) new coordinated behaviours relative to the learners' initial skills could be shown to emerge, and; c) any relationships could be inferred between exploratory behaviour and new skills or better performance.

Notably, in addressing points a) and b), a comparison to the experienced climber's performance in Experiment 1 and Experiment 2 was necessary. In order to maintain equal groups the same number of experienced climbers to that of the learning group were randomly selected from Experiment 1 and Experiment 2 to act the reference group. The data of experienced climbers performance from Experiment 1 were used to compare the performance of the beginners on the transfer tests because these conditions reflect on-sight performance (an important skill that individuals aim to develop in indoor climbing is on-sight climbing). The data of experienced climbers from Experiment 2 were used to determine whether the learners could adapt their immobility and route trajectory to each of the instructional constraints to a similar level as the experienced climbers. Additionally, a qualitative comparison of the body-wall coordination patterns between the groups determined whether similar patterns of coordination were adapted following the intervention.

6.4.2.1 Descriptives with follow-up

Three individuals dropped out of the learning study due to personal reasons (work commitments). Of the individuals who completed testing (seven in total), during the pre-testing, three individuals fell, resulting in four individuals who could finish the route prior to undertaking the 7-week long intervention. The analyses on the pre- and post-tests and learning dynamics is presented below.

6.4.2.1.1 Effect of practice on transfer

In order to determine whether after practice the learners could perform similar to experienced climbers the outcomes of the transfer tests were analysed with respect to the experienced climbers' on-sight climbing performance. Regarding the pre- and post-tests involving the learning route and transfer tests, the descriptive data showed that the beginners' performance on the first on-sight climb on the practice route improved substantially due to practice. Whilst, two participants fell in the pre-test session (these are marked with a red cross in Figure 6.10 below), the participants' who fell, were, after the learning intervention, able to complete the route. Whilst the improvement in performance in the beginners was not as large on the transfer routes in comparison to the practice route, a positive transfer effect is evident in that performance improved across each outcome. However, no clear differences between the transfer routes were evident across any of the outcomes reported. This would suggest that the features of skill that the transfer tests were designed to challenge (route finding in transfer route 1 and graspability in transfer route 2) improved to a similar extent after 7-weeks of practice.

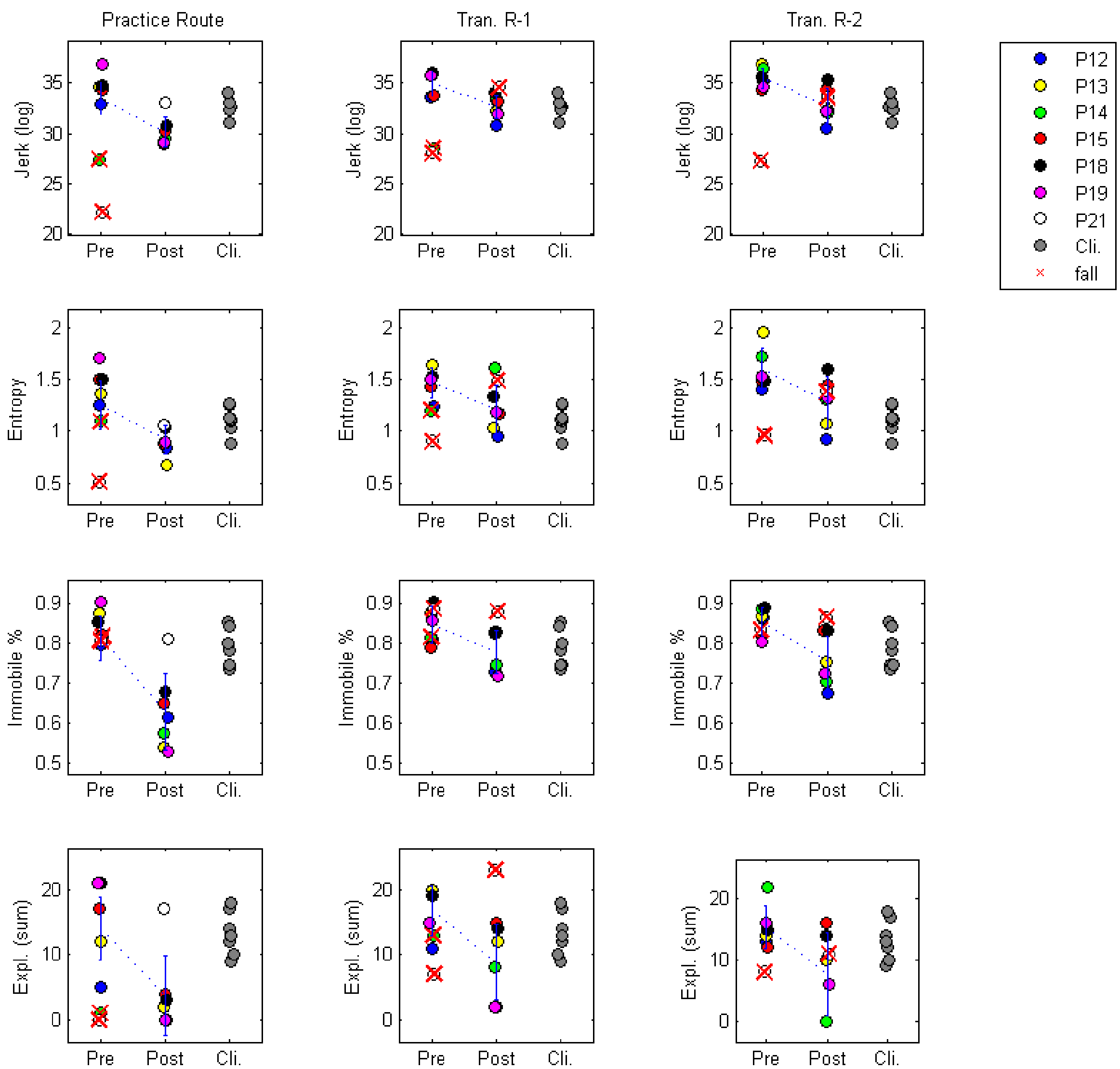

Figure 6-10. Pre- post-test comparisons by route for jerk, entropy, immobility and exploration. Error bars indicate the standard deviation of the climbers who successfully completed each climb. **Cli.** = Experienced climbers **Expl.** = Exploratory actions; **P** = participant; **Tran. R-1** = Transfer route 1; **Tran. R-2** = Transfer route 2. Note that the experienced climber data is based on an on-sight performance on the practice route.

In contrasting the transfer route performance under the post-test conditions with the experienced group of climbers under on-sight conditions, the data suggests that in terms of JCT (top row) that performance under on-sight conditions are at similar levels. Differences in terms of GIE (second row), IMR (third row) and exploratory states (bottom row) suggest a greater extent of within group variability in the learners.

After outlier removal (Participant 21 and Participant 14 being removed from the statistical analysis because their outcome performance was outside the mean by greater than two standard deviations) the results of the repeated measures ANOVA with 2 levels of practice (pre and post) and 3 levels of route (practice route, transfer route 1 and transfer 2) were carried out to confirm the impression from thee descriptive data. Notably, in cases where a significant effect was reported, Helmert contrasts were performed to disambiguate any route effects (comparing the collective variance of the transfer routes to the practice routes in the first round of contrasts and the variance between the two transfer tests in the subsequent round), and these were combined with a simple contrast across the effect of practice to disambiguate any interaction effect(s). In cases where a violation of sphericity were determined, the outcomes with the adjusted degrees of freedom according to the Greenhous-Geisser adjustment have been reported (specifically, Mauchly's test showed up significant for the GIE and exploratory behaviour outcomes for the route effect; respectively, $X^2(2)$ = 6.586, p = .04) and $X^2(2)$ = 6.252, p = .04). Significant effects are reported at equal to and less than 0.05. Additionally, the after practice behaviour of all 7 of the beginners where then compared to 7 randomly selected advanced climbers from experiment 1 on each of the outcome variables for each route. This was done to determine whether after practice the beginners performance behaviours were similar in kind to the advanced individuals. These tests involved independent t-tests. Equality of variance was tested in each case with Levene's test and since no tests were significant, equality of variance was assumed for all subsequent independence t-tests. Significant effects are reported at equal to and less than 0.004 (p value adjusted for the 12 comparisons).

With regards to the outcome of JCT, a significant route effect, F(2,8) = 20.857, p= .001, and a significant practice effect, F(1,4) = 26.701, p= .001, was found. Additionally, a significant route by practice interaction effect was uncovered, F(2,8) = 6.457, p= .021. In follow-up, the Helmet contrasts showed that overall, performance was better on the practice route compared to both the transfer routes $F(1,4) = 25.446$, $p = .007$, but, that performance was not significantly different on the transfer routes, $F(1,4) = 4.092$, $p = .113$. In disambiguating the interaction effect, in comparing the difference between the practice route and the transfer tests, when going from pre-test conditions to post-test conditions and significant contrast was reported, $F(1,4) = 9.736$, $p = .036$. However, in comparing the difference between the transfer tests, when going from pre-test conditions to post-test conditions the contrast was not significant, $F(1,4) = 0.078$, $p = .794$. These data indicating the amount of change due to practice was much larger on the practice route, but, that the amount of improvement between the two transfer tests was not significantly different, although performance did improve. The results of the comparisons between the advanced climbers and the beginners JCT on each route showed that the beginners smoothness was significantly better on the practice route, $t(12)= 3.840$,$p = .002$, but, there were no significant differences between the two groups on either the first transfer route, $t(12)= .433$, $p = .666$, or second transfer route, $t(12)= .476$, $p = .643$. These data indicating that the beginner's on-sight performance on climbing routes graded at a level 5b were similar to advanced climbers in terms of JCT, whereas their performance is even better on a heavily practiced route.

Similar results were uncovered with regards to the main effects on the outcome of GIE, where, a significant route effect, $F(1.06,4.236) = 12.760$, $p= .021$, and a significant practice effect, $F(1,4) = 20.698$, $p= .01$, was found. However, a significant route by practice interaction effect was not shown in the GIE outcome, $F(1.10,4.39) = 3.137$, $p= .099$. Furthermore, in follow-up, the Helmet contrasts showed that overall, performance was better on the practice route compared to both the transfer routes $F(1,4) = 10.856$, $p = .03$, *and*, that in terms of GIE, climbers used a significantly more simplified trajectory on the different on the first transfer route (the one designed with modified hold positions) than the second transfer route (the one deigned with smaller graspable edges), $F(1,4) = 34.262$, p =

.004. These findings suggest that GIE improved at a similar rate across the different routes due practice and that the second transfer route required more complicated route finding compared to the other. The results of the comparisons between the advanced climbers and the beginners GIE on each route showed that the beginners entropy was not significantly better on the practice route, $t(12) = 2.656, p = .021$, the first transfer route, $t(12) = 1.418$, $p = .182$, or second transfer route, $t(12) = 1.852$, $p = .089$. These data can be interpreted similar to the JCT outcomes indicating that the beginner's on-sight route finding performance on climbing routes graded at a level 5b were similar to advanced climbers in terms. Additionally the trend of an improved GIE in the beginners on the practice route is also clearly evident.

With regards to the outcome of IMR, these data followed the same trends as the out JCT reported above, where, a significant route effect, $F(2,8) = 37.368$, $p < .001$, and a significant practice effect, $F(1,4) = 22.536$, $p = .009$, was found. Additionally, a significant route by practice interaction effect was also uncovered, $F(2,8) = 12.366$, $p = .004$. In follow-up, the Helmet contrasts showed that overall, performance was better on the practice route compared to both the transfer routes $F(1,4) = 56.474$, $p = .002$, but, that performance was not significantly different on the transfer routes, $F(1,4) = 16.350$, $p = .016$. In disambiguating the interaction effect, in comparing the difference between the practice route and the transfer tests, when going from pre-test conditions to post-test conditions and significant contrast was reported, $F(1,4) = 9.736$, $p = .036$. However, in comparing the difference between the transfer tests, when going from pre-test conditions to post-test conditions the contrast was not significant, $F(1,4) = 0.687$, $p = .454$. These data indicating the amount of change due to practice was much larger on the practice route, but, that the amount of improvement between the two transfer tests was not significantly different, although performance did improve. The results of the comparisons between the advanced climbers and the beginners JCT on each route showed that the beginners smoothness was significantly better on the practice route, $t(12) = 3.854$, $p = .002$, but, there were no significant differences between the two groups on either the first transfer route, $t(12)= .236$, $p = .818$, or second transfer route, $t(12)= .529$, $p = .607$. Again, these data can be interpreted similar to the JCT and GIE outcomes in that the beginner's on-sight continuity of movement on climbing routes graded at a level 5b were similar to advanced climbers in terms. Again, the tendency to increase mobility on the practice route compared to the advanced clambers was also evident.

Finally, with regards to the outcome of exploration, a there was no route effect reported, $F(1.07,4.27) = 5.829$, $p= .068$, however, a significant practice effect was uncovered, $F(1,4) = 26.304$, $p= .007$, was found. Additionally, there was not a significant route by practice interaction, $F(2,8) = 3.351$, $p= .088$. In follow-up, the Helmet contrasts showed that overall, the exploratory behaviour was lower on the practice route compared to both the transfer routes $F(1,4) = 8.654$, $p = .042$, but, that exploration was not significantly different on the transfer routes, $F(1,4) = 1.261$, $p = .324$. These data indicating the amount of change due to practice was much larger on the practice route, but, that the amount of change in exploration between the two transfer tests was not significantly different, although it did significantly reduce. The results of the comparisons between the advanced climbers and the beginners exploratory behaviour on each route showed that the beginners exploratory behaviour was significantly reduced on the practice route, $t(12)= 3.650$, $p = .002$, but, there were no significant differences between the two groups on either the first transfer route, $t(12)= .779$, $p = .451$, or second transfer route, $t(12)= 1.886$, $p = .089$. These data can be interpreted similar to the JCT, GIE and IMR outcomes in that the beginner's on-sight continuity of movement on climbing routes graded at a level 5b were similar to advanced climbers in terms. Again, the tendency to increase mobility on the practice route compared to the advanced clambers was also evident.

6.4.2.1.2 Effect of practice on coordination and performance flexibility

In order to address whether new coordinated behaviours relative to the learners' initial skills could be shown, and whether these behaviours beared a resemblance to experienced climbers, the data from the pre- and post-test scanning procedure were analysed in detail.

With regard to the coordination patterns adopted during the scanning procedure (referring to Figure 6.11), these data provided good qualitative evidence that each of the individual learners acquired a new movement pattern or in some respects could be said to have reorganised the nature of their coordination repertoire in response to the scanning procedure constraints. Specifically, as predicted, the hip-wall angle showed that during states of mobility, each individual could use the face-wall coordination pattern both in the pre- and post-test sessions. This suggests that the face-wall pattern is spontaneously available to beginners without the need for prior experience or practice within an indoor climbing context. With regards to the side-wall pattern, participants during the pre-test appeared to either favour one side of the body (Participants 12, 13, 15, 18 and 19) or were entirely unable to use a side-wall coordination pattern whilst mobile (Participant 14 and Participant 21). This data suggests most of the individuals at the beginning of the study might be considered as bi-modal because they could use both a face-wall and one side of the side-wall state space at the outset of practice. Furthermore, in the cases of Participants 14 and 21, at the beginning of practice these individuals might better be described as uni-modal.

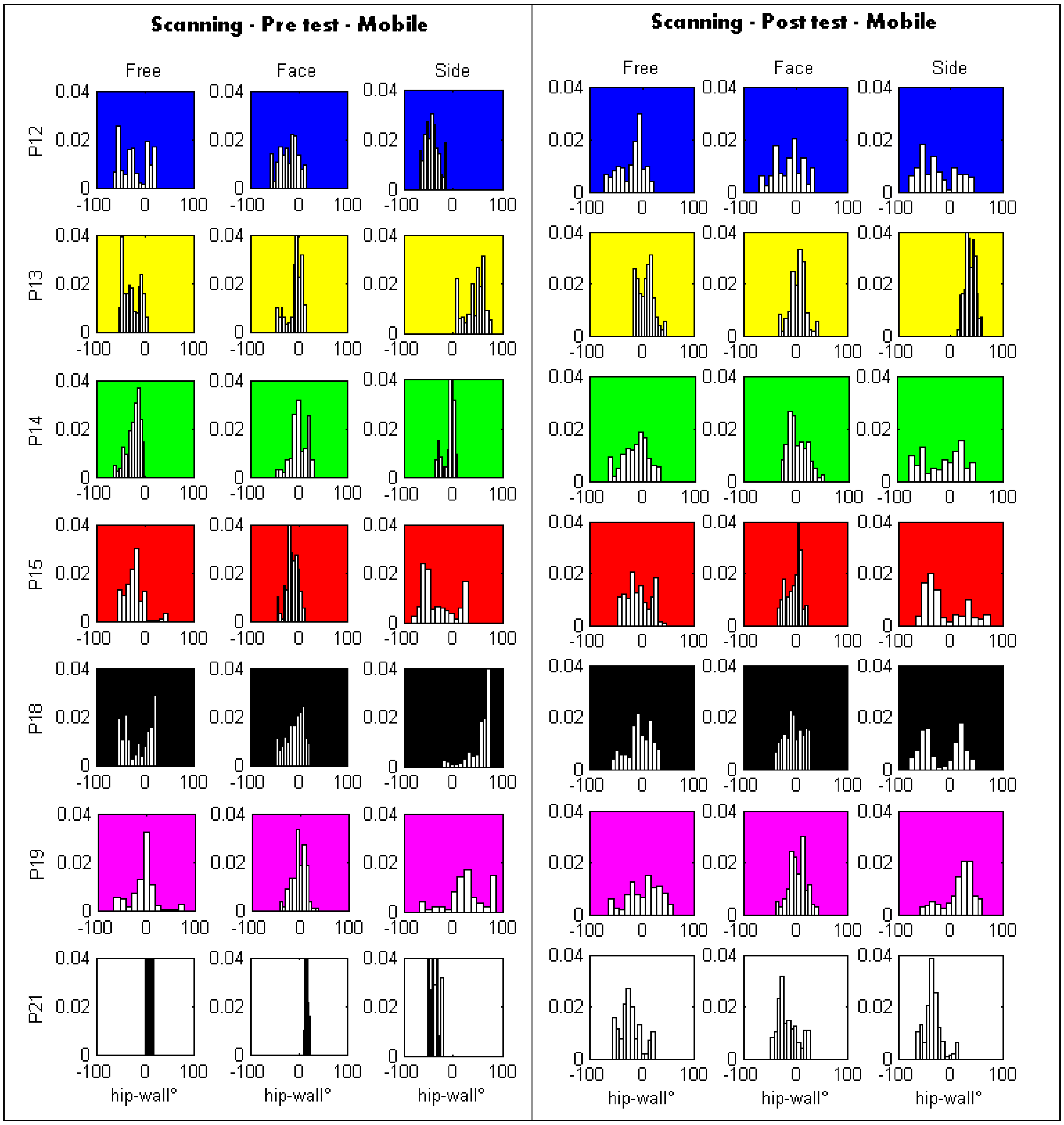

Figure 6-11. Hip-wall angle during mobility for each individual for each condition of scanning under pre- and post-test conditions.

The major difference between the pre-test and post-test conditions was that in the condition where individuals were asked to climb side-on-to-the-wall, a bi-modal distribution is evident in the post-test, whereas, previous to the learning intervention, a uni-modal distribution best fit the data (an impression which is particularly evident in Participants 12, 14, 15 and 18). Notably, Participants 13 and 21 appeared to show a unimodal distribution both in the pre-test and post-test. These data suggesting that to the learners' coordination repertoire generally went from either a bi-modal to a tri-modal characterisation. The exceptions to this included: the case of Participants 13, who remained bi-modal (but notably with a reorganisation to the opposite side); the case of Participant 14, who went from a uni-modal to a bi-modal characterisation; and the case of Participant 21, who appeared to remain uni-modal.

The ability of the learners to maintain smoothness under the different conditions of the scanning procedure, and to what extent this corresponded to the experienced climbers was then considered. The data, shown in Figure 6.12 only partially supports the hypothesis that the learners would acquire similar adaptive behaviour to the experienced climbers. In the post test, the learner group appeared to have been unable to able maintain smoothness across the three conditions (top row in Figure 6.12), suggesting that the side-wall coordination pattern was not as adaptive as the experienced climbers. Similar to the experienced climbers, the learners showed a tendency to increase trajectory complexity (middle row in Figure 6.12) when asked to climb side-to-the-wall in the post test, however, adaptation in mobility was not observed (bottom row). This suggests that the reason the smoothness was not maintained across conditions was that that the intervention did not lead to the same coupling between mobility and trajectory complexity.

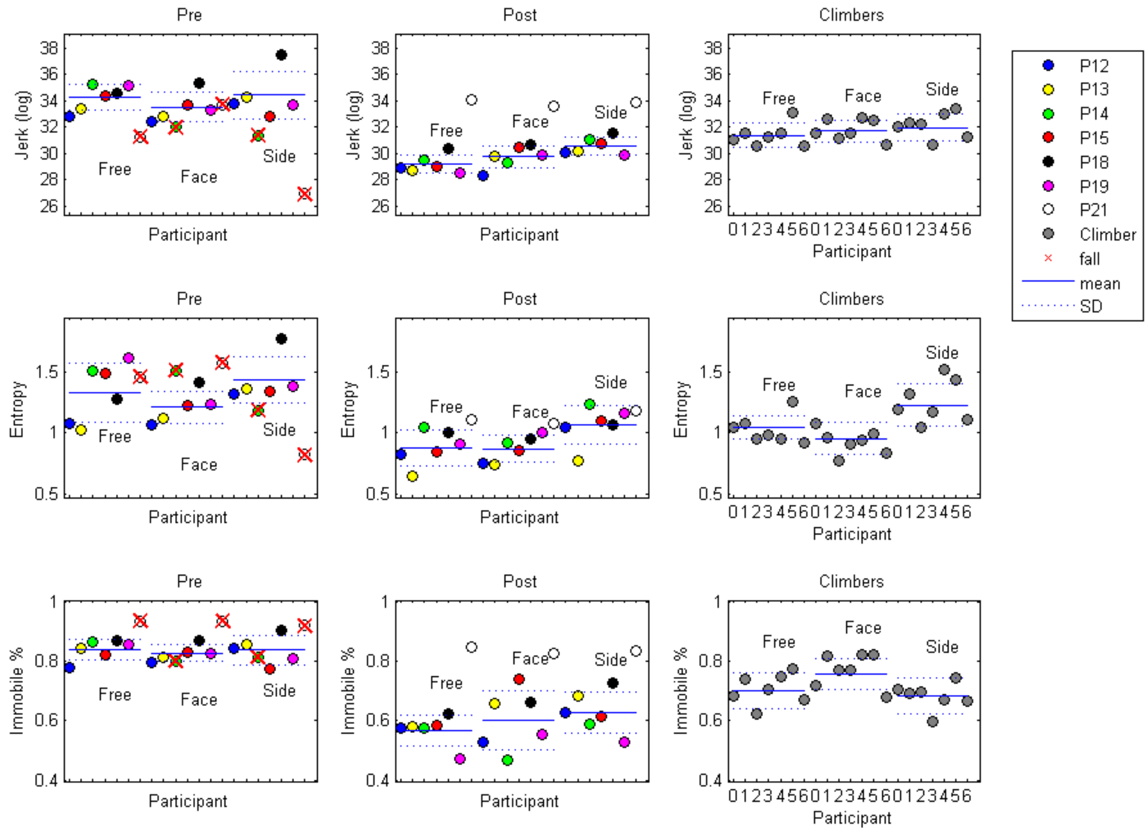

Figure 6-12. Scanning procedure pre- post-test comparison. **SD** = standard deviation. Note that mean and standard deviations excluded fallers and participant 21.

However, it is worth pointing out that because the scanning procedure was carried out on the practice route, the substantial amount of practice probably influenced the nature in which the beginners performed on the route, despite the different instructions. Future research adopting scanning procedures in pre-, post-test fashion should account for this, and, utilise a separate route to that of the intervention.

<u>6.4.2.1.3 Individual learning dynamics</u>

The outcomes JCT, GIE, IMR and exploratory behaviour for the seven individuals throughout all trails of practice are presented in Figure 6.12. The data shows that with practice all outcomes generally decreased suggesting a broadly linear improvement in performance with practice. The JCT showed a greater between individual consistency than GIE and IMR. This is perhaps because, as shown in

Experiment 2, individuals co-adapt these dimensions for climbing smoothly. The exploratory actions at the limbs whilst for some individuals, appear to completely resolve, for others, take a fluctuating characteristic. Indeed the data suggests substantial individual differences during practice, where it is clear that there are some trials where an individual's performance abruptly differ to the overall group.

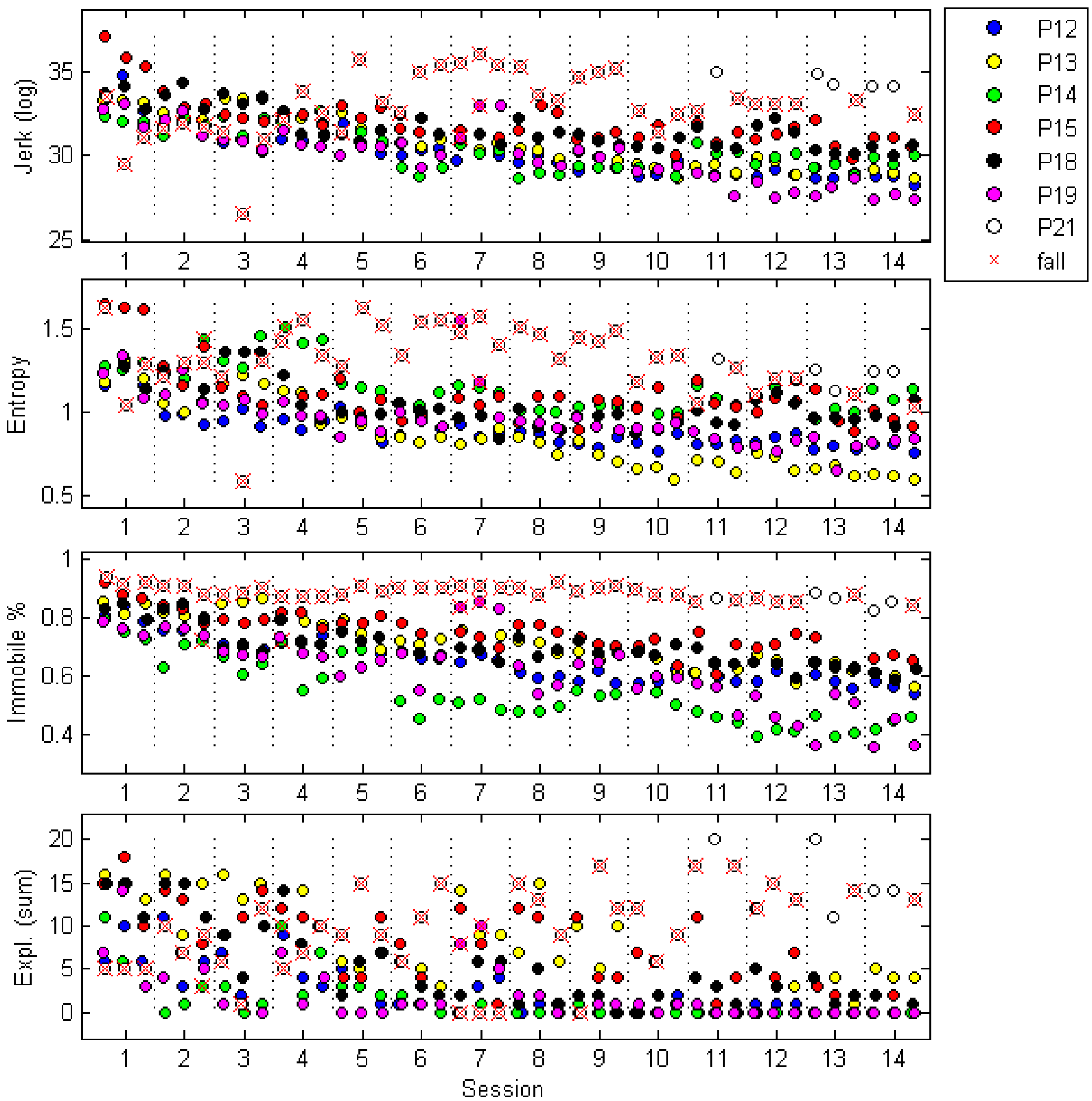

Figure 6-13. Individual outcomes across each trial of practice. **Expl**. = exploratory actions; **P** = participant.

In plotting each individual's learning curves on the outcome variables, it was evident that different learning curves were needed to effectively fit each individual (for an overview see Figure 6.18 below). Specifically, in examining each of the individual learning curves, four type's curves were apparent: 1) a general linear improvement (Participant 15, seen below in Figure 6.14); 2) a general linear improvement with transient worsening (Participant 12 and 19); 3) a lack of change marked by a sudden improvement in performance (Participant 13, 14 and 18), and; 4) a worsening in performance (Participant 21).

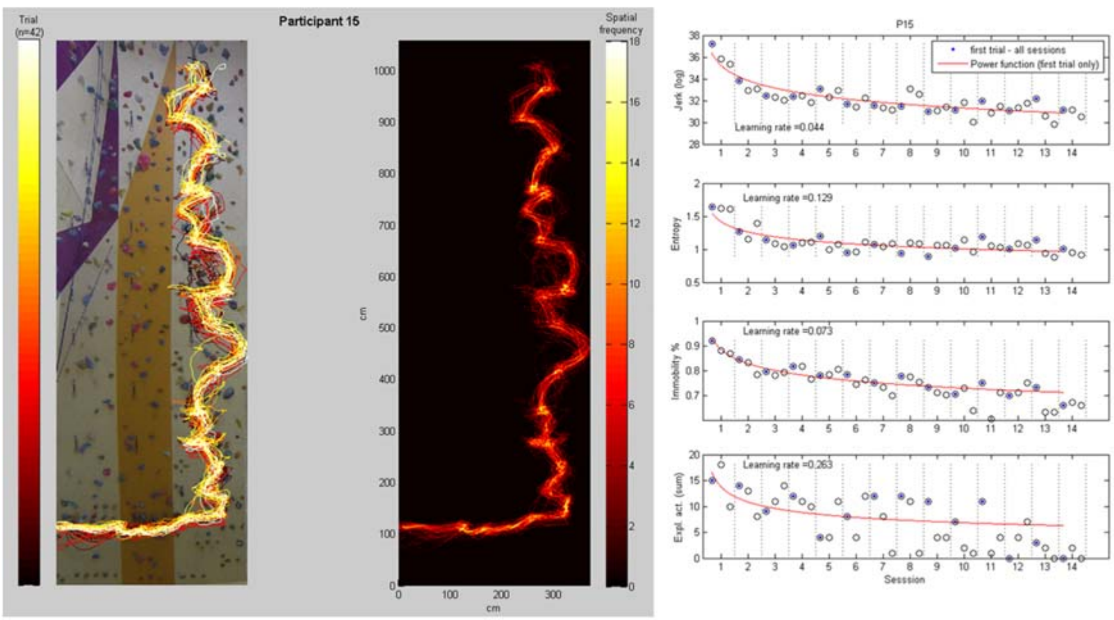

Figure 6-14. Learning dynamics of Participant 15 who showed a continuous linear improvement. **Expl. act.** = number of exploratory actions at the limbs. **cm** = centremetres. **P** = participant.

Participants 12 and 19 were both similar to Participant 15, to the exception that these individuals showed a period of sudden worsening in performance followed again by a general linear improvement (refer below to Figure 6.15 for the example of Participant 12, and the Supplementary Material for Participant 19s learning curves).

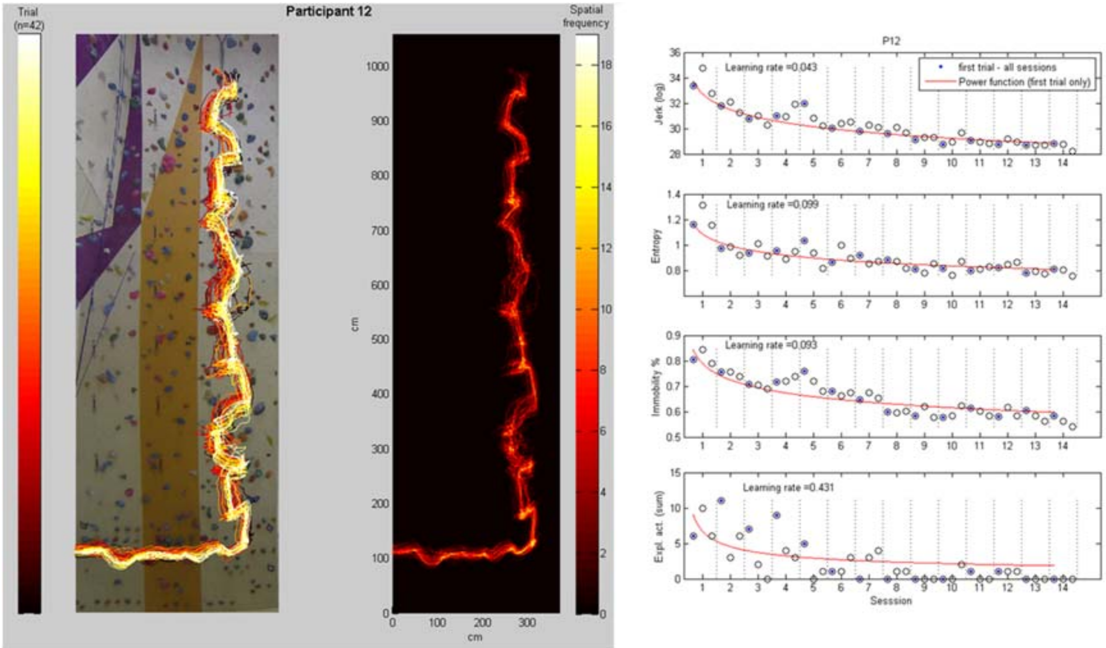

Figure 6-15. Learning dynamics of Participant 12 who showed a linear improvement in performance but transient worsening in performance at Session 5. **Expl. act.** = number of exploratory actions at the limbs. **cm** = centremetres. **P** = participant.

Figure 6.16 shows the learning dynamics of Participant 14 (which was similar to Participant 13 and 18, see Supplementary Material and Figure 6.18 below) as an example of a learning curve suggesting a lack of change marked by a sudden improvement in performance. The learning curve of Participant 14 suggesting that a break point emerged between Sessions 5 and 6 in JTC, requiring a new line fit to the characterise the learning dynamics.

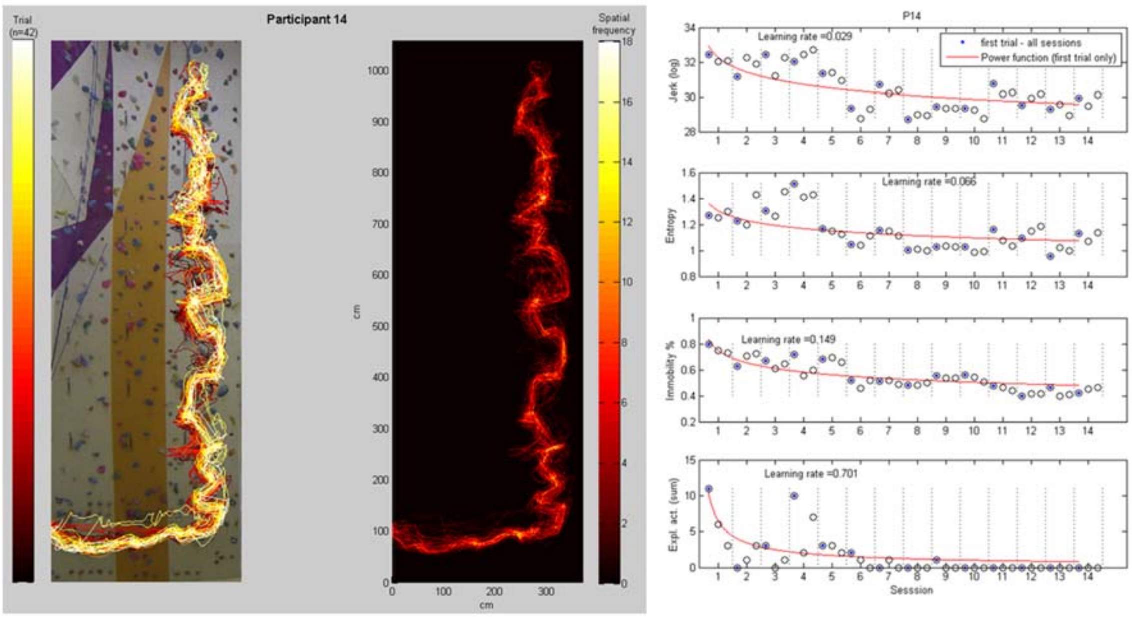

Figure 6-16. Learning curves for Participant 14 exemplifying a lack of improvement followed by an abrupt improvement. **Expl. act.** = number of exploratory actions at the limbs. **cm** = centremetres. **P** = participant.

Finally, Participant 21 showed a unique learning curve in that this individual's performance *worsened* with practice (Figure 6.17). For, Participant 21, this effect, where jerk worsened, was most likely due to this individual being unable to successfully complete the route for an extended period of time and subsequently, performance worsened the higher up this individual advanced (refer to the trial-by-trial trajectory data in Figure 6.17). Indeed, it was not until Session 11 that the route was successfully completed by Participant 21.

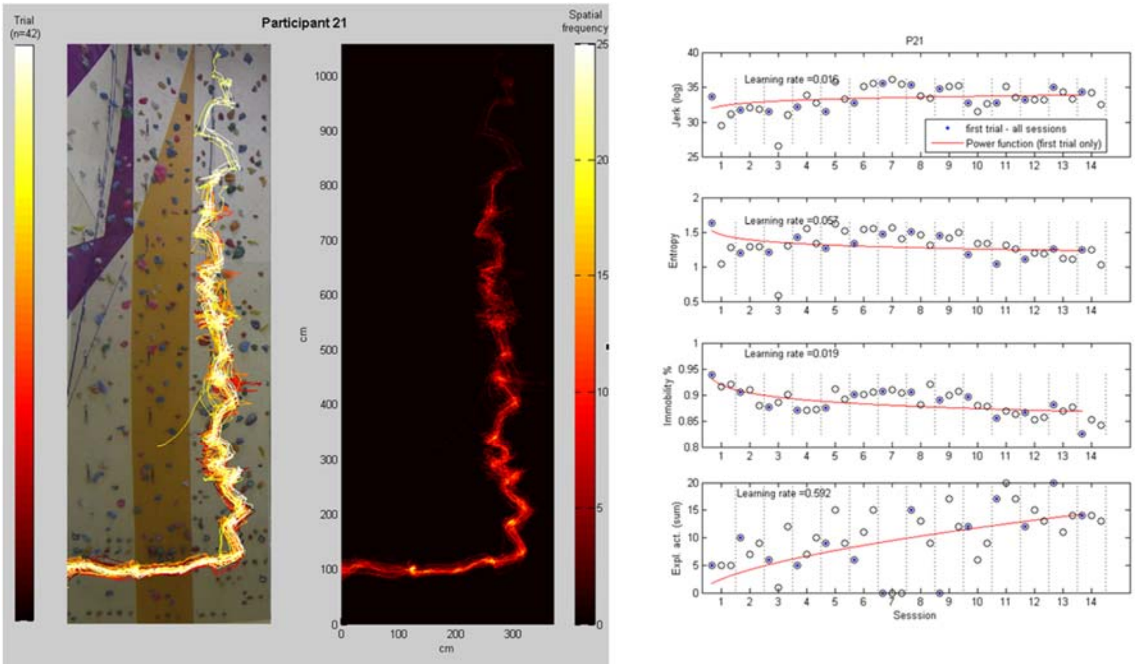

Figure 6-17. Learning curves for Participant 21 who worsened with ongoing practice. **Expl. act.** = number of exploratory actions at the limbs. **cm** = centremetres. **P** = participant.

Although the data indicates that individuals show different learning curves, despite this, a commonality across all individuals was that an abrupt change in performance could be identified. For example, taking the maximum differential between each first trial of each session on the outcome of JCT yielded candidate break points for each participant that generally agreed with visual inspection (see Table 6.4).

Table 6-4. Break points.

P. ID	Break Point Auto[a]	Break Point Manual[b]	Curve Type
12	S. 5-6	S. 5-6	Type 2
13	S. 5-6	S. 5-6	Type 3
14	S. 6-7	S. 5-6 & 6-7	Type 3
15	S. 1-2	S. 1-2	Type 1
18	S. 6-7	S. 4-5	Type 3
19	S. 4-5	S. 7-8	Type 2
21	S. 6-7	S. 6-7	Type 4

a: method used was the detected maximum differential between the first trials of successive sessions; b: method used was visual inspection. **P** = participant. **S** = session.

After determining potential breakpoints each individuals JCT were plotted using two function either side of the break points. The results presented below in Figure 6.18 show that primarily for the individuals who appeared to show a large change in performance between sessions (curve type 3, see Table 6.4) two types of line fits with a break point appear to be a good choice. However, for Participants 12 and 15, the break seem no real improvement on a logarithmic fit. Interestingly, the individual who went on to achieve the best smoothness, shows an improved fit with the breakpoint. Finally, the same can be said for Participant 21showing an inverted U curve.

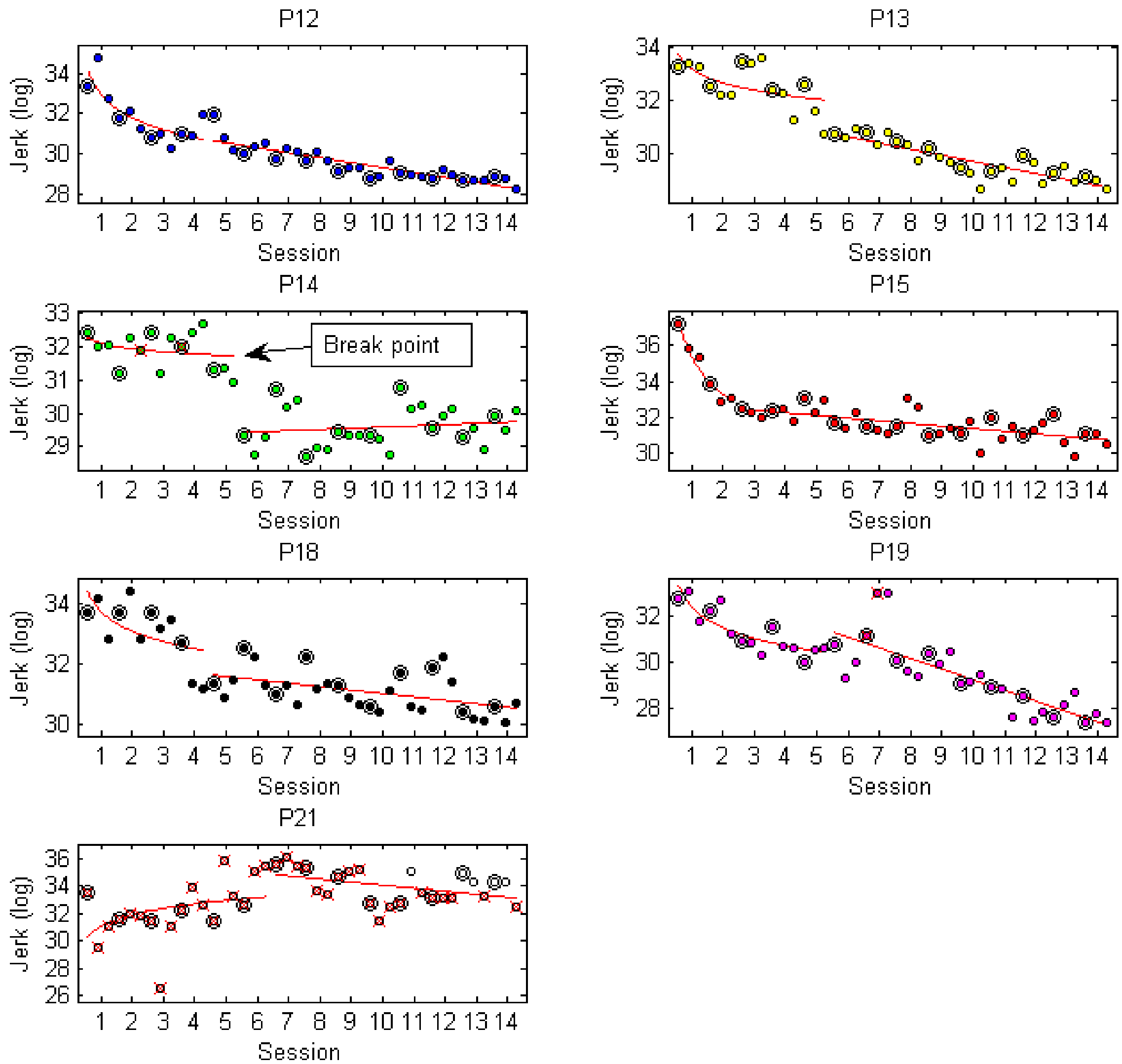

Figure 6-18. Individual learning curves with break points.

Another concern at the outset of this experiment was whether performance improvement could be related to exploratory behaviour. Whilst exploratory behaviour was evident during the learning, it primarily evident at the beginning of practice and did not appear be related to break points or the learning curves.

6.4.2.2 Key findings Experiment 3

The aim of experiment 3 was to determine if after practice under representative constraints, individuals that could be considered in coordination stage of learning would be facilitated to acquire a new more advanced pattern of coordination. It was shown that prior to learning, most of the participants could be considered either with a mono- or bi-stable coordination repertoire and that, after practice modified their intrinsic dynamics. The study was also concerned with showing whether after extensive practice under representative conditions beginners would exhibit similar behaviour to those of experienced climbers. However, the same degree of flexibility was not evident in how these individuals adapted to the different instructional conditions. No clear link between the learning dynamics and the learning outcomes in this study, suffice to say that individuals showed different dynamics, in some cases a generally linear improvement in performance was observed, whereas in other individuals, a transition-like improvement in performance was observed.

Findings are generally in agreement with existing research that have previously demonstrated in multi-articular task learning, individuals can display different responses during learning to a given set of constraints which may influence the nature and/or rate of learning (de Vries, Withagen, & Zaal, 2015; Liu, Mayer-Kress, & Newell, 2006; Teulier, Nourrit, & Delignières, 2006; Vegter, Lamoth, de Groot, Veeger, & van der Woude, 2014). For example, Nourrit et al., (2003) observed five beginners over 39 trials of practice revealing at the individual level of analysis examples of: linear improvement; transitional; and, complete lack of improvement. In this study, all individuals could be said to have improved. Even Participant 21 who showed worse jerk at the end of the learning intervention, clearly improved performance given that the route was eventually completed.

6.5 Conclusions

The purpose of this experiment was to test whether multi-articular performance in specific ecological performance contexts requires specific experience and whether practice under conditions that represent meta-stability can facilitate the acquisition of coordination similar to individuals who naturally acquired their skills. This study showed that key ideas from complex systems approaches generalise effectively to a whole body physical setting. Specifically, intrinsic dynamics were shown to have a strong influence on the behavioural tendencies adopted by beginners and without affecting performance. Furthermore, under specific task constraints, it was shown that existing coordination patterns can be tested to identify whether an individual needs practice in order to acquire such movement patterns. Specifically, in climbing the ability to move dynamically whilst the body is orientated to the side of the wall was shown to be a specific pattern of coordination that some beginners need practice to acquire. It was also demonstrated that during climbing, both movement frequency and complexity are used by experienced individuals to maintain performance as constraints are varied. When practicing under conditions that represent meta-stability, individuals appear to spontaneously explore, allowing them to acquire new movement patterns without explicit instruction. The learners in this study also showed a positive transfer both in terms of using holds in different positions (transfer of route finding) but also for holds with less explicit grasping opportunities.

Meta-stability appears to be an effective property to represent in practice design for the purpose of supporting spontaneous exploration that can support the emergence of more advanced patterns of coordination in complex physical activity tasks. Future research needs to address the role of existing skill on the transfer of learning, and more specifically, whether enhancing exploration during practice can improve learning outcomes by considering multiple groups with routes that might constrain exploration in different ways. Finally, it’s possible that similar levels of positive transfer could have been achieved with less practice, this suggests that multiple transfer tests might be useful to administer throughout a practice intervention.

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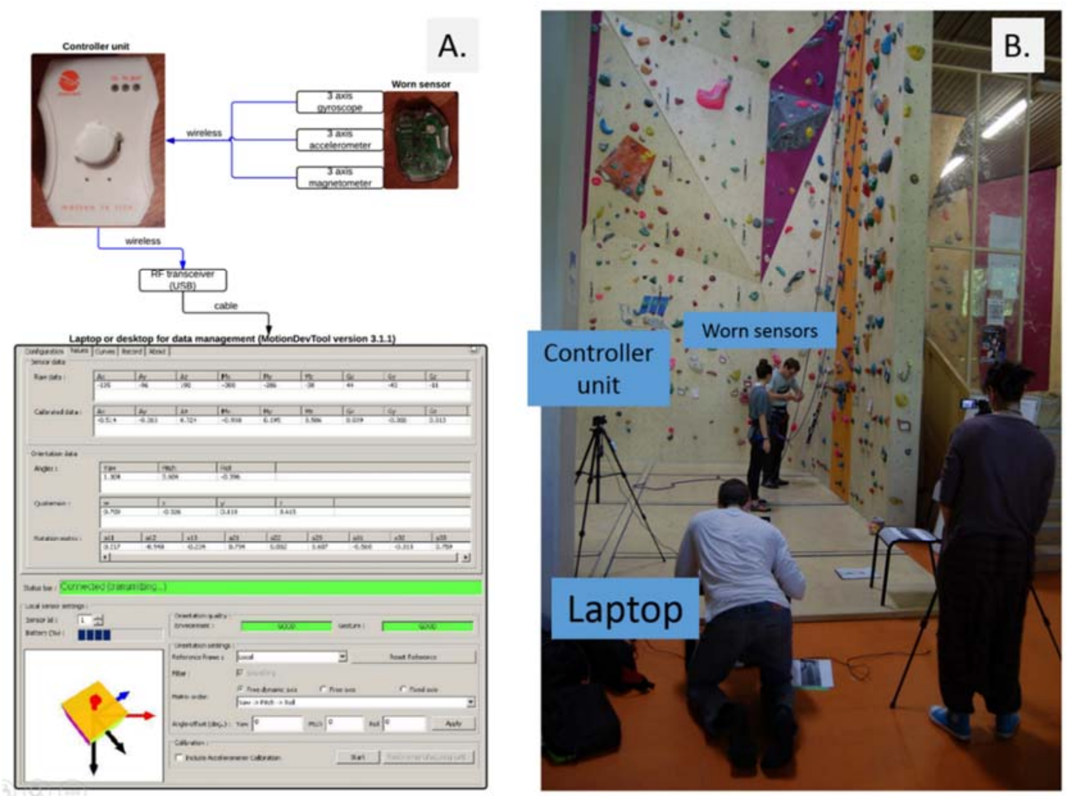
Supplementary Material for Chapter 6

Supplementary Methods

Instrumentation of Inertial Measurement Units

We used inertial measurement units (IMUs) that corresponded to a combination of a tri-axial accelerometer (±8G), tri-axial gyroscope (1600°.s^{-1}) and a tri-axial magnetometer (*MotionPod*, Movea©, Grenoble, France). Data collected from the IMUs were recorded with North magnetic reference and at a 100 Hz sample frequency. Data is transmitted wirelessly to a control unit and recorded with a software package (with *MotionDevTool*, Movea©, Grenoble, France, see Panel A. showing the control flow for acquisition) run off a windows operating system. See Panel B., in the figure below for the hardware components in the data collection context.



Supplementary Figure S6-1. Experimental environment and control flow for the inertial measurement units.

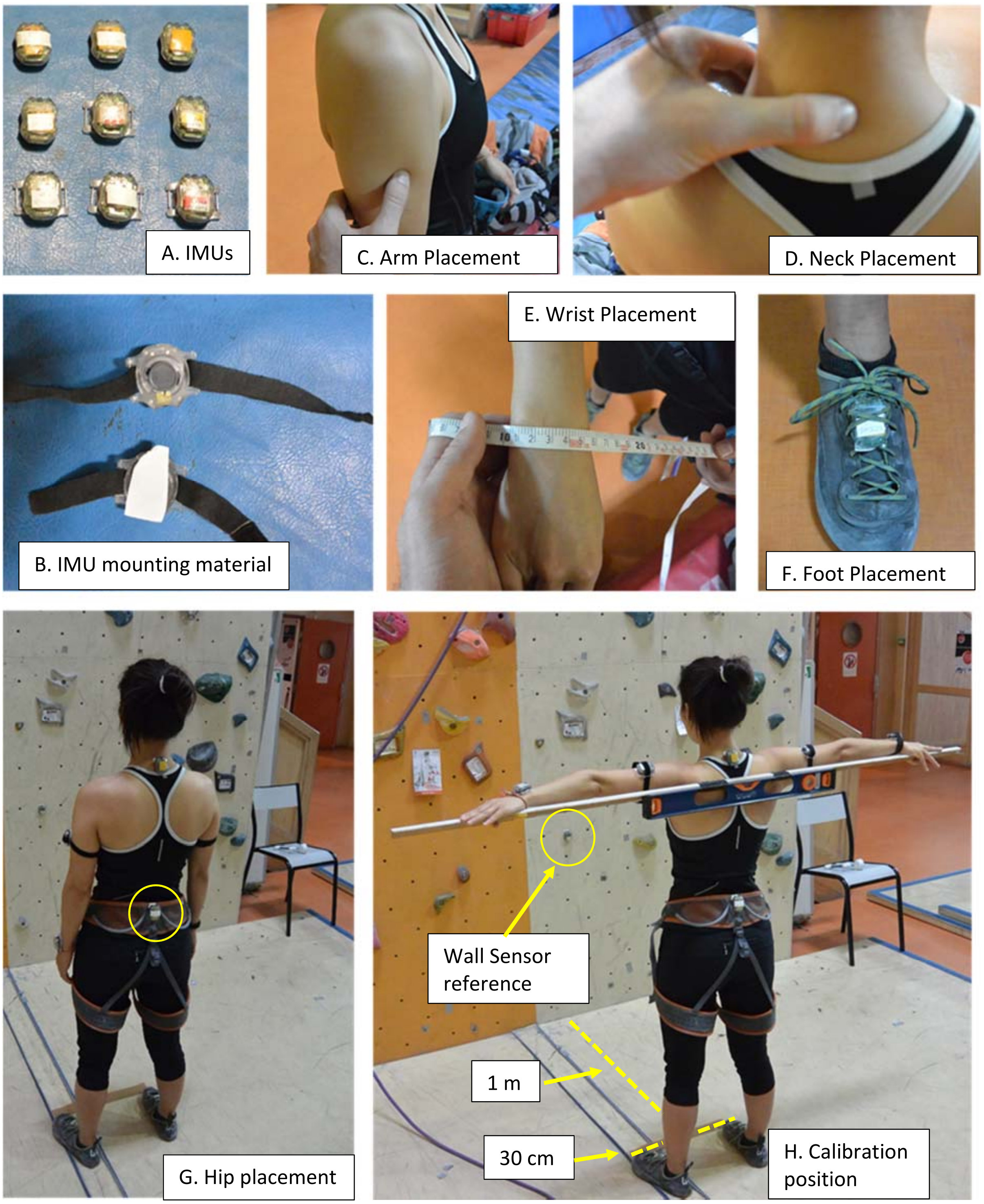
Placement procedures

Individual IMUs were attached to eight locations on the body with reference to anatomical landmarks that could be identified though palpation and that catered for practical concerns (including ensuring the climbing movements would not be interfered with, stability of the location (minimising the amount of underlying muscle)). These same sensors and their relative placement locations, orientations and procedures were used throughout the entirety of the experimentation. See the summary in the table and figure below for the placement procedures.

Supplementary Table S6-1.

IMU placement location	Details	Reference
Neck	Attached over the 7th cervical vertebra at the spinous process and at the longitudinal axis of the body midline.	See Supplementary Figure S6-2, Panel D.
Hip	Attached to the harness at the longitudinal axis of the body midline.	See Supplementary Figure S6-2, Panel G.
Left wrist	Attached midway between the distal radial styloid process and the ulnar styloid process on the posterior surface of the left lower arm.	See Supplementary Figure S6-2, Panel E & Panel H.
Right wrist	Attached midway between the distal radial styloid process and the ulnar styloid process on the posterior surface of the right lower arm	See Supplementary Figure S6-2, Panel E & Panel H.
Left foot	Attached to shoe tongue of the left shoe under the second row laces from the top. Laces were drawn over the top of the sensor to increase the security of its position.	See Supplementary Figure S6-2, Panel F & Panel H.
Right Foot	Attached to shoe tongue of the right shoe under the second row laces from the top. Laces were drawn over the top of the sensor to increase the security of its position.	See Supplementary Figure S6-2, Panel F & Panel H.
Left arm	Attached over the deltoid insertion of the left arm.	See Supplementary Figure S6-2, Panel C & Panel H.
Right arm	Attached over the deltoid insertion of the right arm.	See Supplementary Figure S6-2, Panel C & Panel H.
Wall	Attached to the wall plane that was climbed. (note that the a recording of 30 seconds was made on a single occasion and, because, this signal was a sufficient reference in any cases where the climbers orientation with respect to the wall needed to be known, the sensor was subsequently removed).	See Supplementary Figure S6-2, Panel H.

Note: the sensors were in all cases attached with the same orientation by locating the button of the sensor to always face vertically. In all cases sensors were secured using a double sided adhesive. Additional security was obtained in the cases of the upper limb sensors with Velcro strapping (see Supplementary Figure S6-2, Panel B).



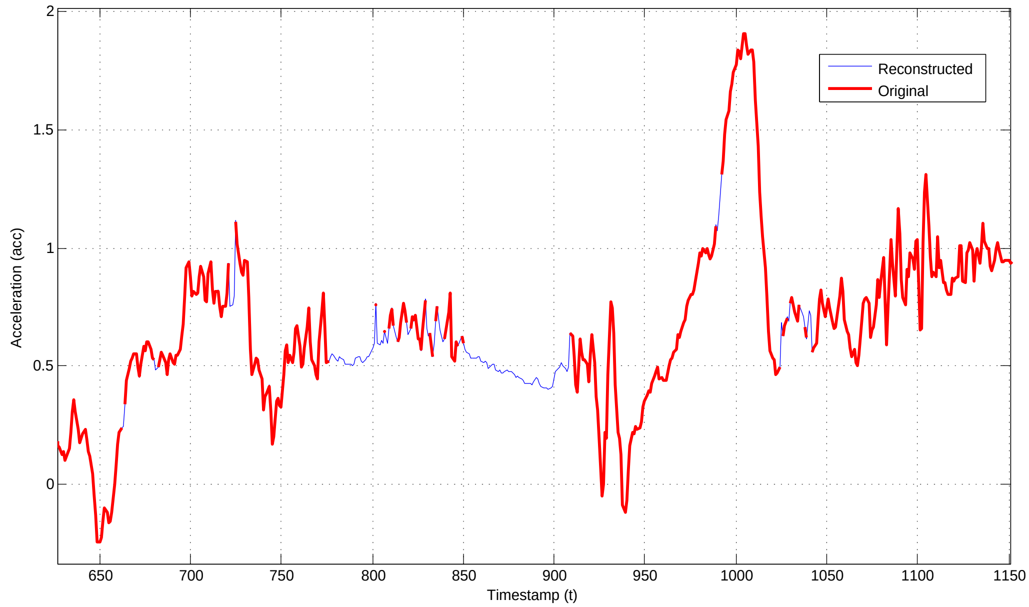
Supplementary Figure S6-2. Inertial measurement units mounted to participants during the experiments conducted in Study 2.

Recording procedures

Prior to commencing data acquisition participants were required to hold a specific body position at the same physical location and orientation with respect to the climbing wall (shown in Supplementary Figure S6-2, Panel H). An additional IMU was also placed on the experimental climbing wall to locate it on the Earth reference and with respect to the sensors placed on the participants (also shown in Supplementary Figure S6-2, Panel H). Prior to commencing data collection, participants were required to stand in a 'T' reference position for 10 seconds. Use of the same location and orientation of the limbs with respect to the wall was ensured by having the participants stand with the tips of their toes at the edge of a 30 cm long strip of tape placed parallel to the wall at a distance of 1 m. Additionally, a water level attached to a long stick and held by the participants with palms facing the ground (as shown in in Supplementary Figure S6-2, Panel H). After holding the calibration position for 10 seconds, the participants could then apply chalk to their hands and then adopted the beginning position. This required taking hold of the first old with both hands and using two starting foot holds and remaining stationary for five seconds. They were then asked to commence, the time just prior to movement onset marking the beginning point of each climb. At the end of the climb individuals were asked to touch the last hold of the route with both hands. The frame where the second hand was discerned as making contact with the hold marking the end of the trial.

Accounting for missing data

Prior to performing computations on the collected data any applied algorithms need to be robust to missing data. For instance some missing data in sensor recordings inevitably occurs due to distance and the emitting power of the device. An efficient missing value imputation algorithm based on missing value imputation in low-rank matrices by solving the nuclear norm minimization problem was therefore applied (Vicci, 2001). An example of imputing missing values in time-series is shown in the following figure.



Supplementary Figure S6-3. Imputation of missing data in sensor time series due to transmission loss.

Accounting for drift

A major concern was that raw accelerometer readings cannot be used directly during computation due to orientation changes during the ascent. The solution to this problem was by tracking sensor orientation using a complementary filter based algorithm (Madgwick, Harrison, & Vaidyanathan, 2011), which integrated the three sensor information sources (i.e., accelerometer, gyroscope and magnetometer). Specifically, whilst the gyroscope measured precise angular changes at very short time durations it could not be used to track the angle changes by integration due to a drift issue. Additionally, the accelerometer provided absolute, though noisy, measurements of hip acceleration and the Earth's gravitational force at the same time. Following Madgwick et al., (2011), by combining the two sensor information sources it was possible to reduce drift of the gyroscope for hip orientation tracking. Finally, when magnetometer information was added, it was possible to compute orientation of the sensor with respect to the fixed frame of Earth reference (magnetic North, East and gravity directions).

Computation of the trunk with respect to the wall

To evaluate the orientation of the climbers trunk relative to the wall during climbing we computed the neck, hip and climbing wall orientation (a 3D frame, constituted by three 3D unit vectors) with respect to the Earth reference (magnetic north, East and gravity directions) by using a complementary filter-based algorithm, which integrated the three sensor information sources (i.e., accelerometer, gyroscope and magnetometer) (Madgwick et al., 2011). Then, the angular time series corresponding hip rolling motion around the vertical axis were extracted according to the climbing wall reference: 0° of roll corresponds to face-wall position; positive angle values of roll correspond to left side-to-the wall positions (e.g., -90° corresponds to left perpendicular trunk position to the wall); negative angle values of roll correspond to right side-wall positions (e.g., 90° corresponds to right perpendicular trunk position to the wall). Note that the average of the sensor orientation data during the ten seconds were then used to offset the orientation data collected during climbing.

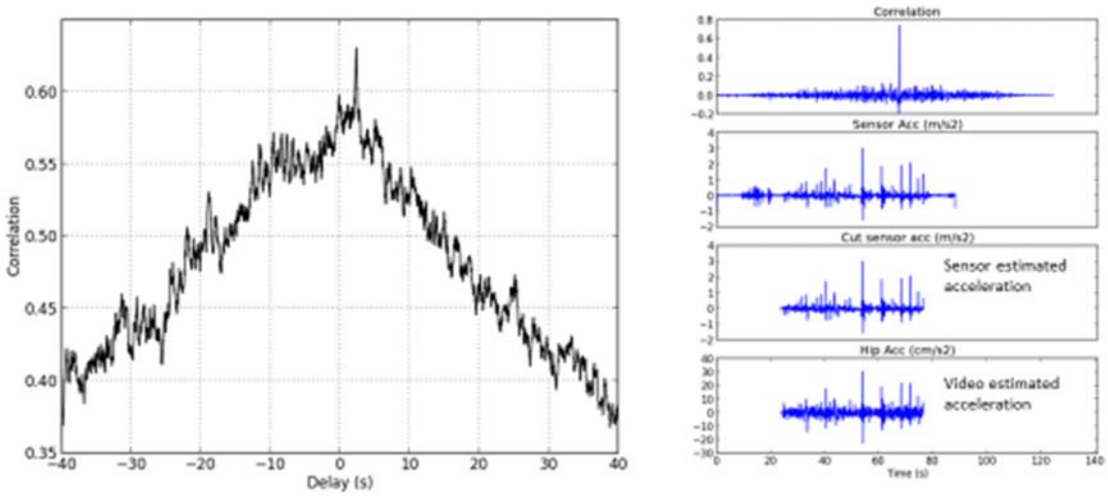
Instrumentation of the image capture

In order to perform calculations on each participant global climbing trajectory we detected the position of the hips with respect to the wall plane during each climb. To do this, participants were equipped with a battery operated commercially available light (we found that for automatic tracking purposes, using a red light and was tremendously superior to a white light) (Bishop & Welch, 2001). The light was mounted on to the climbing harness at the body midline (the same harness was used throughout the experimentation. Specifically, a classical Kalman filter was used to track the red light on a frame by frame basis, and an adaptive filter was implemented to counterbalance similar colours in the surrounding environment (in this case, the presence of televisions in the recorded picture). Once the red-light position on the image was obtained, lens distortion had to be corrected, this followed by parallax correction. In both cases Corrections were based on manually determined points in the field of view (taking into account co-linearity and co-planarity assumptions) and their known relative distances that were then used in the subsequent transformation (Kaehler & Bradski, 2013). Video footage of each ascent was captured with a frontal camera (goPro) fixed 9.5m away from the climbing wall and at a distance of 5.4m from the ground (see Supplementary figure below). The go-pro was then operated wirelessly using a purpose built remote (see Supplementary Figure below), recordings at 60hz were stored for later extraction directly to a SD card.

Supplementary Figure S6-4. Camera recording hardware, corrections and automatic tracking results.

Synchronisation

Because the camera and sensors were not synchronised, the delay between the frame-based detection of the hip position and the acceleration from the worn sensor had to be estimated. In order to synchronise the signals we first obtained trajectory from the video, a time series of the acceleration of the pelvis. Then, using a maximum correlation measure between the sensor-based lateral and vertical accelerations of the pelvis, the delay between each signal (video and sensor) was estimated. Once this delay was obtained, the start and end points then manually determined from the video and the two signals extracted overt the same time period. An example of maximum correlation determined lag and subsequent hip and sensor based acceleration is presented in the Supplementary Figure below.



Correlation and the time lag between signals

Outcomes of applying the delay at the maximum correlation

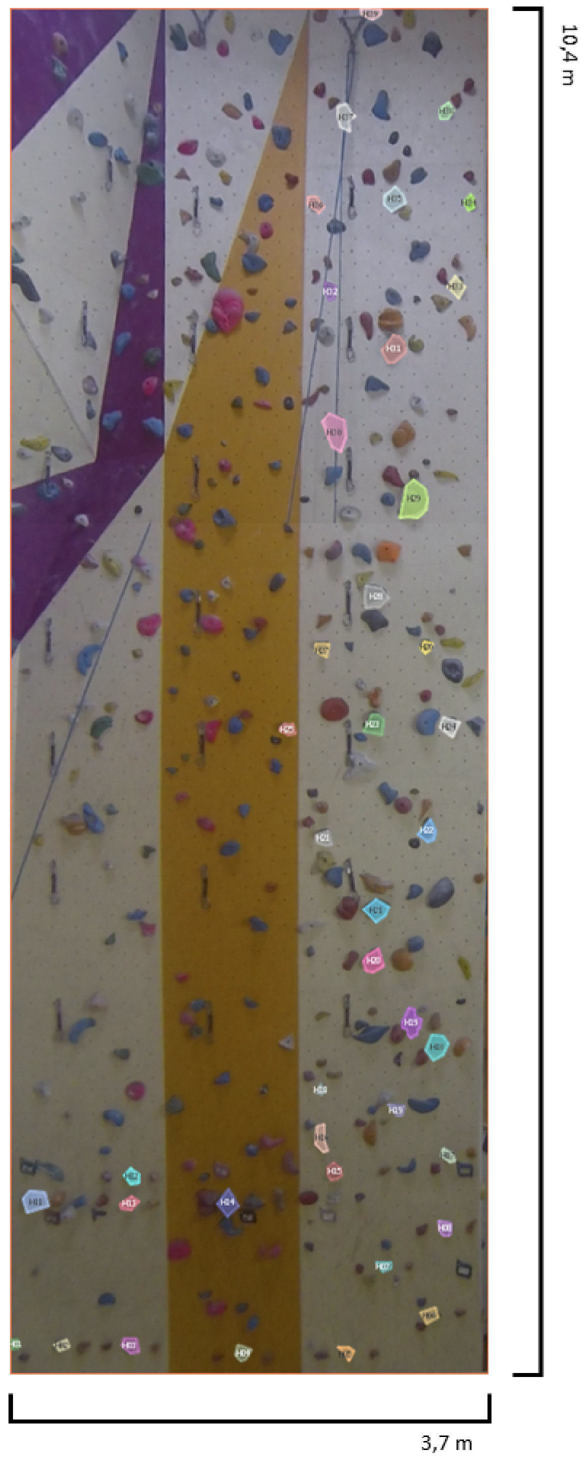
Supplementary Figure S6-5. Synchronisation of the sensor and video based time series.

Route design

Route used for:

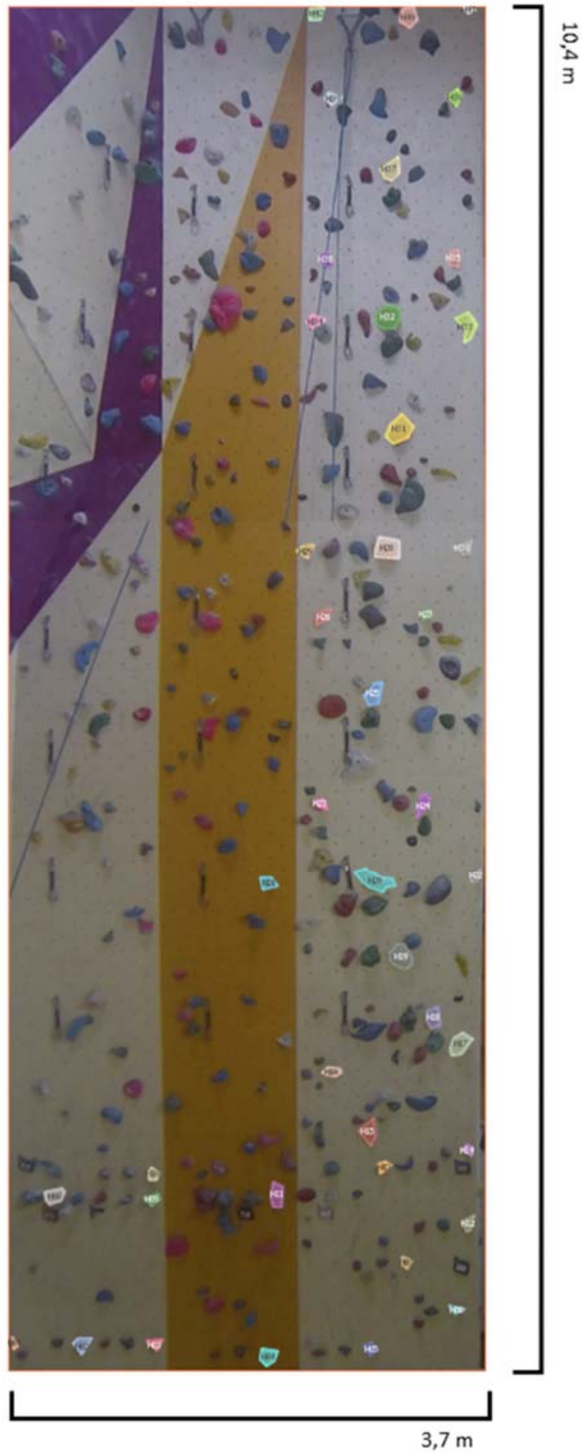
Experiment 1;
Scanning proceedure
(Experiments 2 & 3), and; the
practice route (Experiment 3).

Number of holds = 39
Width = 3,7 m
Height = 10,4 m
Inclination = 90° to the horizontal
F-RSD = 5b



Supplementary Figure S6-6. Route used in Experiment 1, the Scanning Procedure (Experiments 2 & 3) and for the practice route in Experiment 3.

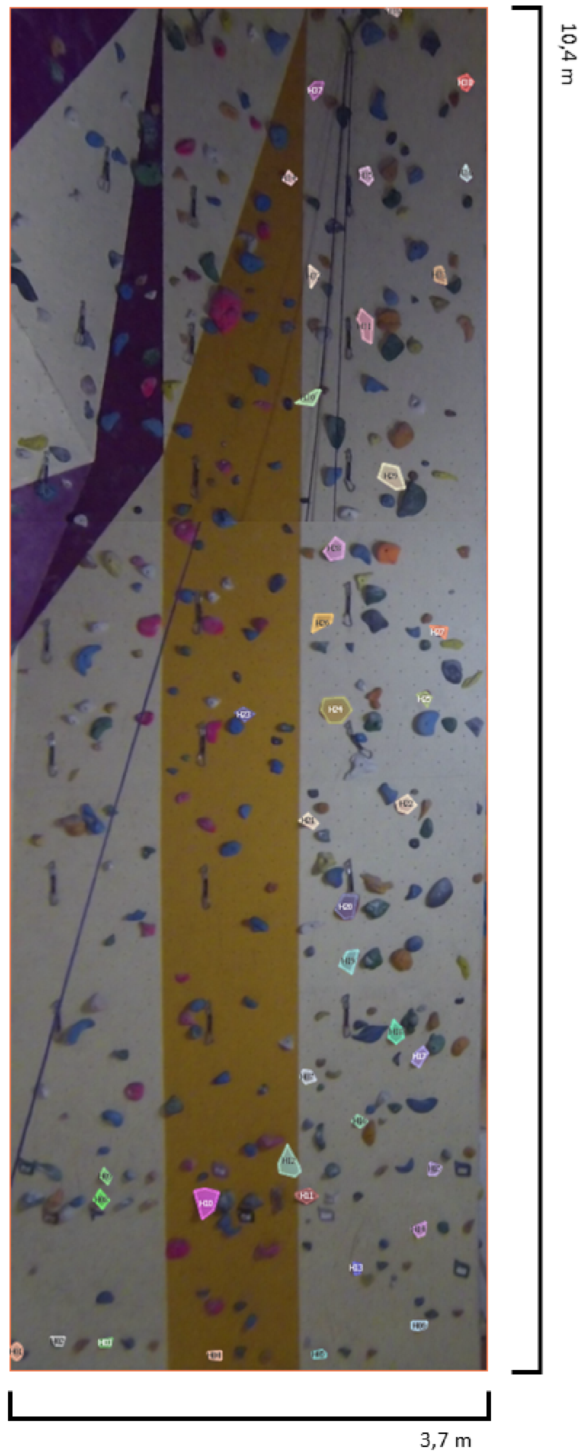
Route used for:
- Experiments 3, Transfer test, holds in unique positions (Route 1)
- Number of holds = 39
- Width = 3,7 m
- Height = 10,4 m
- Inclination = 90° to the horizontal
- F-RSD = 5b



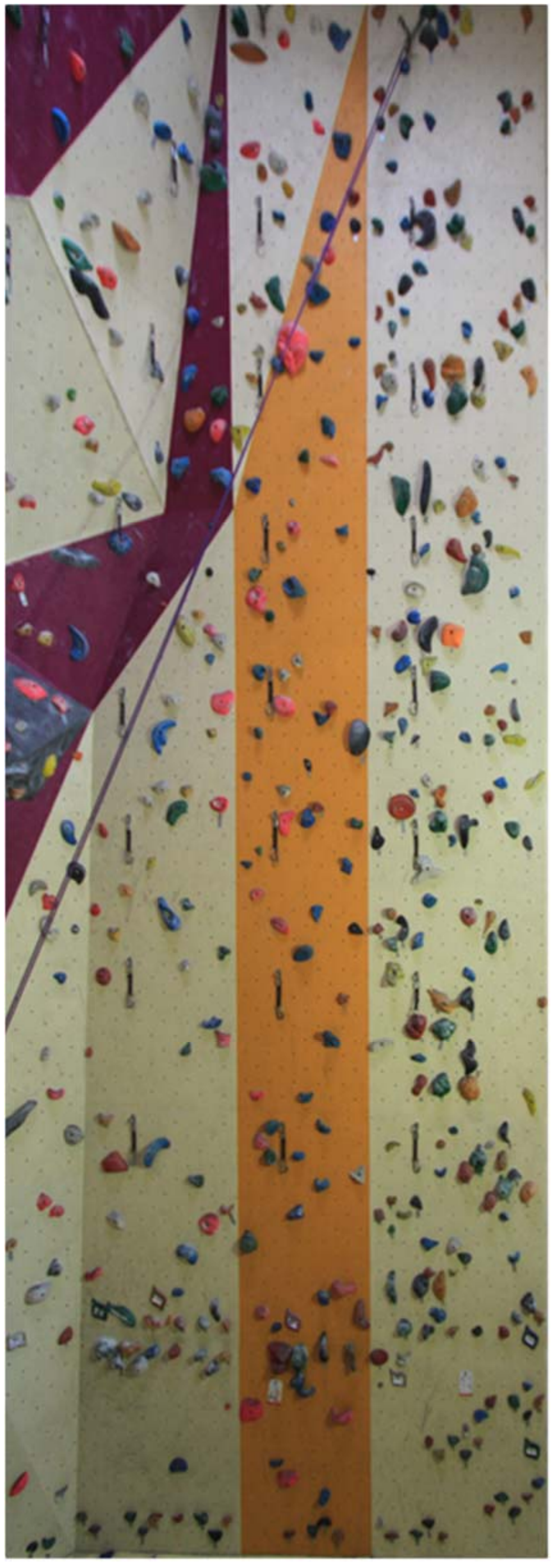
Supplementary Figure S6-7. Transfer test route used in Experiments 3. Holds were placed in different positions relative to the practice route.

Route used for:

Experiments 3, Transfer test, holds with smaller graspable surfaces (Route 2)
Number of holds = 39
Width = 3,7 m
Height = 10,4 m
Inclination = 90° to the horizontal
F-RSD = 5b

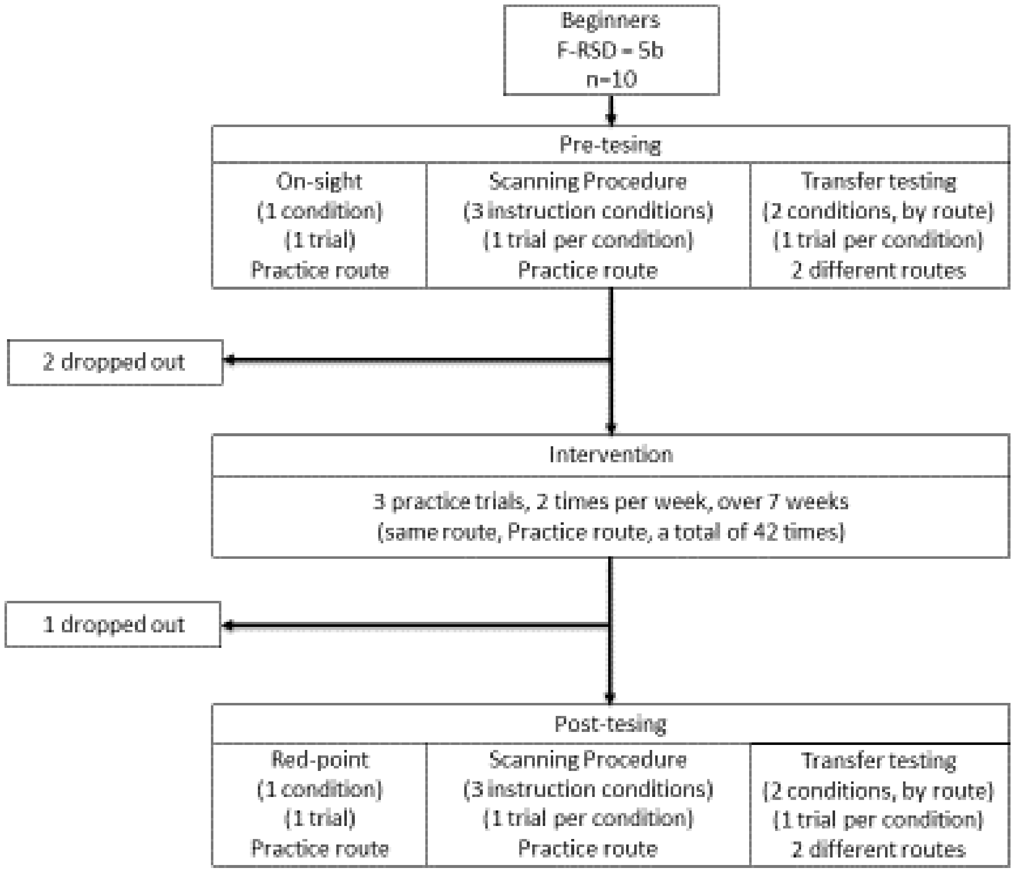


Supplementary Figure S6-8. Transfer test route used in Experiments 3. Holds were designed with smaller graspable edges relative to the practice route.



Supplementary Figure S6-9. Uncorrected image of the routes used for Study 2.

Study design



Supplementary Figure S6-10. Experimental design, Experiment 3.

Supplementary Data

Supplementary Table S6-2. Participant details for Experiment 1.

	Experienced climbers (n = 9)	Firefighters (n = 9)	Inexperienced climbers (n = 9)
Age (yrs)	29.2±7.5	28.1±3.6	20.2±2.2
Experience (yrs)	13.5±5.7	1.3±1.6	1.7±0.9
On-sight ability (Ewbank)	24.5±1.5	17. ±.5	17.1±0.3
Height (cm)	173.9±5.4	172.8±7.3	165.9±8.8
Arm-span (cm)	175±4.7	173.2±8.0	167.7±11.2
Overhead reach (cm)	223.1±7.6	222.3±8.0	214.5±12.4
Body mass (kg)	63.9±8.6	67.5	60.3±10.7
Height weight ratio	2.7±0.3	2.6±0.3	2.8±0.4
Grip strength (kg)	57.4±8.8	53.5±12.5	35.7±14.6
Grip strength to body mass ratio	0.91±0.2	0.80±0.1	0.58±0.2

cm = centremetres; kg = kilograms; yrs = years. Note: values represent the average and standard deviation.

Supplementary Table S6-3. Participant details for Experiment 2.

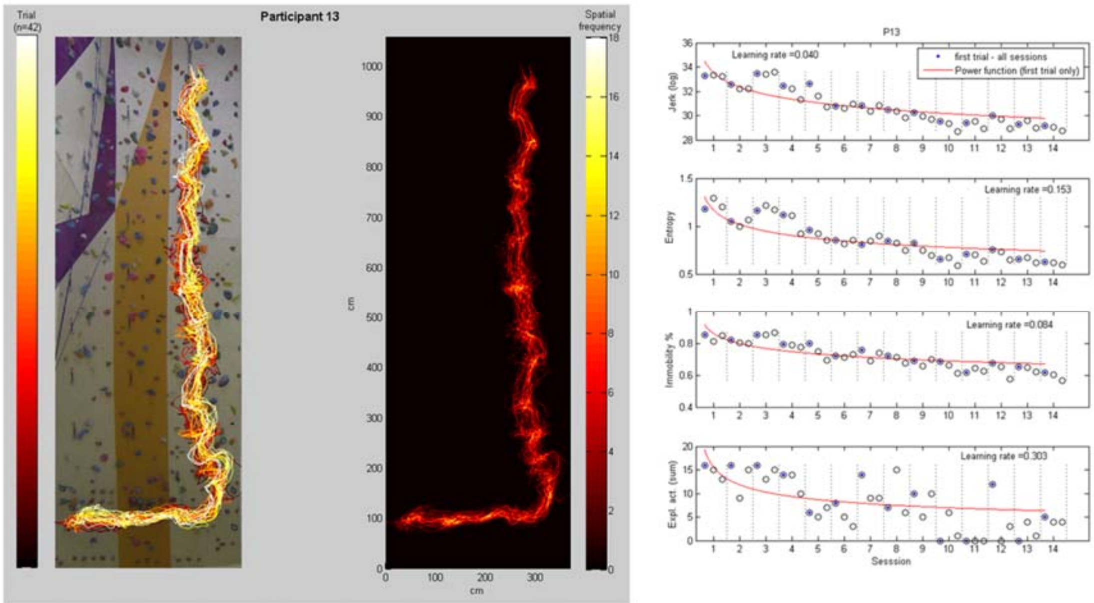
	Experienced climbers (n = 10)	Inexperienced climbers (n = 10)	Fallers (n = 5)
Age (yrs)	27.6±7.6	25±5.2	22.6±3.7
Experience (yrs)	11.3±5.7	1.9±1.3	1.2±1.1
On-sight ability (Ewbank)	23.9±1.6	17.4±0.5	17.2±0.4
Height (cm)	172.8±6.3	172.4±7.4	165±7.5
Arm-span (cm)	174.7±6.3	174.7±7.7	163±9.8
Overhead reach (cm)	223.3±9.6	221.6±7.7	212.5±12.9
Body mass (kg)	63.3±9.8	66.2±8.2	62.1±12.6
Height weight ratio	2.8±0.4	2.6±0.3	2.7±0.4
Grip strength (kg)	58.9±7.9	51.0±14.9	35.3±10.9
Grip strength to body mass ratio	0.95±0.22	0.76±0.19	0.57±0.1

cm = centremetres; kg = kilograms; yrs = years. Note: values represent the average and standard deviation.

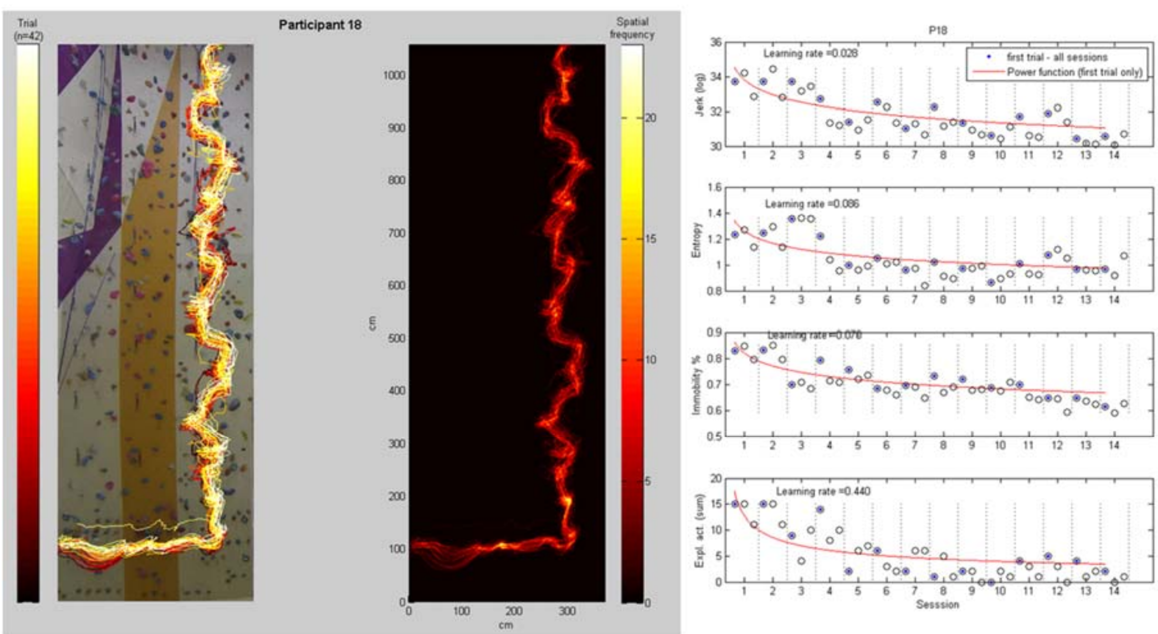
Supplementary Table S6-4. Participant details for Experiment 3.

	P12	P13	P14	P15	P18	P19	P21
Age (yrs)	18	19	21	20	22	24	18
Experience (yrs)	0.5	0	0.5	1	1	2	0
On-sight ability (Ewbank)	17	17	17	18	17	165	16
Height (cm)	162	182	176	171	156	165	163
Arm-span (cm)	162	185	173	178	152	166	166
Overhead reach (cm)	209.7	233.7	226.6	222.4	204.6	216.3	213.5
Body mass (kg)	54.6	68.4	83	58.5	53	2.5	59
Height weight ratio	3.0	2.7	2.1	2.9	2.9	58	2.8
Grip strength (kg)	26.2	54.6	52	26	23.8	58	22.5
Grip strength to body mass ratio	0.48	0.80	0.63	0.44	0.45	0.88	0.38

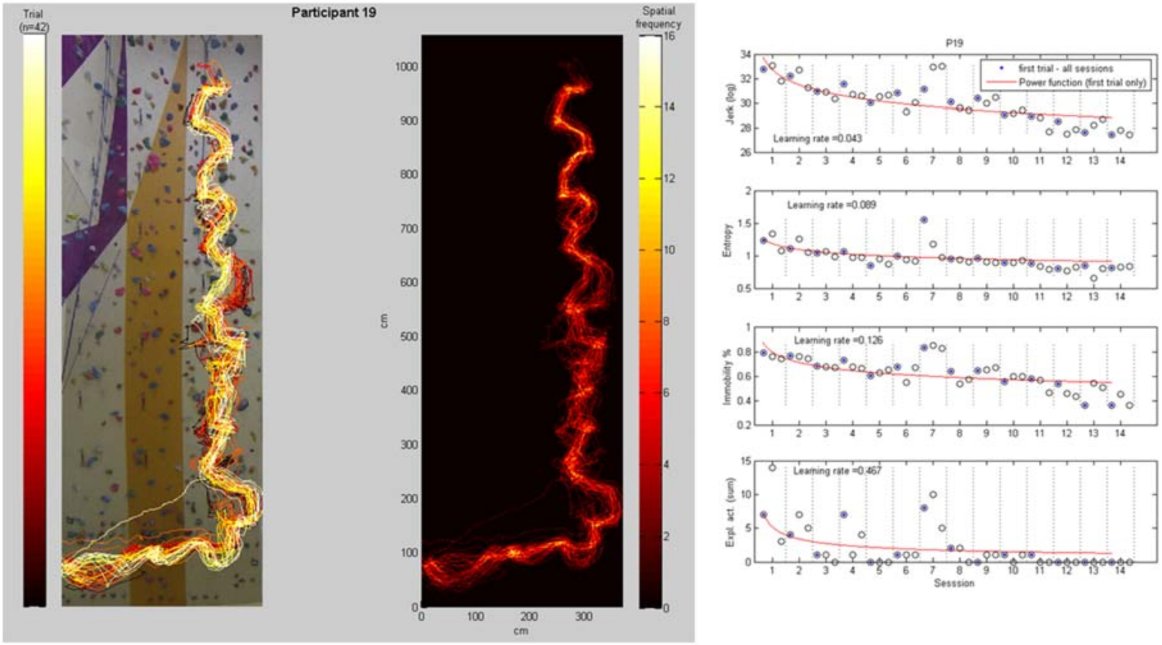
cm = centremetres; kg = kilograms; yrs = years.



Supplementary Figure S6-11. Learning dynamics of Participant 13 who showed a continuous linear improvement. **Expl. act.** = number of exploratory actions at the limbs. **cm** = centremetres. **P** = participant.



Supplementary Figure S6-12. Learning dynamics of Participant 18 who showed a continuous linear improvement. **Expl. act.** = number of exploratory actions at the limbs. **cm** = centremetres. **P** = participant.



Supplementary Figure S6-13. Learning dynamics of Participant 19 who showed a continuous linear improvement. **Expl. act.** = number of exploratory actions at the limbs. **cm** = centremetres. **P** = participant.

Supplementary References

Bishop, G., & Welch, G. (2001). *An introduction to the Kalman filter*. Paper presented at the Paper presented at the Proceedings of the ACM Computer Graphics Conference (SIGGRAPH-2001), Los Angeles, California, USA. .

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CHAPTER 7. DISCUSSION

Summarising findings

Table 7-1. Chapter 7 Table of contents.

7.1 General discussion

The previous chapters (Chapters 2-6) presented the main results of the thesis. This chapter reviews the most important findings of the thesis as an integrated body of work, and presents an integrated ecological dynamics framework for undertaking constraint manipulation for learning and skill transfer within the climbing domain.

7.1.1 Key findings from the thesis

Based on literature review (Chapter 2), I discussed how skill should be conceptualized as an emergent property that involves an exploration of the systems inherent degeneracy. This review showed that transfer of skill that is on the basis of informational constraints can be understood in terms of general and specific mechanisms. However, there are uncertainties in whether principles of learning uncovered in simple tasks can also be adapted in complex physical activity contexts. These uncertainties arise from the nature of experimental designs in observing learning behaviour involving tasks that to do not resemble the sorts of contexts individuals normally seek to participate and not evaluating the outcome of learning or intervention based on transfer tests. I therefore proposed how experimental design might be best establish representative learning design for promoting new skill learning by establishing a meta-stable regime through constraint manipulation.

Based on the findings from theoretically driven work in simple coordination tasks, I also recommended that in order to confirm representative design research can demonstrate individuals are able to achieve similar skills as individuals who have 'naturally' (without artificial intervention) acquired their skill by using transfer tests and scanning procedures. I, therefore, proposed that high priorities should be placed on research that can sample motor learning and transfer in complex physical activity and sport environments with active communities of expert participants.

Participation in many physical activities pertains to tasks that nest cyclical locomotor behaviour with a rich mixture of discrete actions. In addition to this concern is that the transfer of skill within and across different domains of practice lacks empirical evidence. I, therefore, proposed climbing as a research vehicle, being a task requiring both locomotion and discrete actions with many sub-disciplines through which to test questions of transfer (Chapter 3). This review used a systematic approach to uncover the key constraints on skilled coordination in climbing. Experienced individuals exhibit a clear advantage in detection and use of climbing affordances when visually inspecting a route from the ground and when physically moving though a route.

Two directly measurable features of skilled climbing have been suggested to bear a relationship, where, coordination of the climber with respect to the climbing surface and movement fluency. The literature provides little direct evidence as to how coordination patterns are acquired in climbing and in what way learning processes can be enhanced. Some findings however link exploratory behaviour induced by modulating task difficulty as improving performance with practice. In this respect, the variation of the physical properties of hand holds and wall slope inclination have been clearly linked as key parameters influencing difficulty or promoting different coordination patterns in climbing tasks.

Many different approaches have been reported in the literature for observing climbing skill and there has been little attempt in the literature to integrate a consistent theoretical framework of learning when adopting these measure. Thus, I conducted a review of the key spatial-temporal parameters that characterise skilled performance and evaluated their theoretical implications and limitations (Chapter 4). Whilst, both spatial and temporal parameters appear to show considerable variation across study designs, the overarching goal of climbing is understood to be smooth or fluid transition through a route.

The variability reported in spatial and temporal parameters is in some way explained by how a climber's intentions can change in relationship to the experimental constraints imposed by different study designs and include the various wall design and skill levels examined. Intentions were shown to be estimated in performatory and exploratory behaviour, the literature providing some details regarding how intentions can change as function of skill or task design. Further research is needed to understand how spatial and temporal co-relate to climbing smoothness and whether practitioners can guide individuals to effectively couple spatial and temporal parameters through influencing constraints on intentions.

Most previous studies designed to evaluate meta-stability in complex multi-articular tasks have used experienced individuals and have not reported trial effects. However, if learning is induced in experienced individuals, observation of behaviour over repeated trials of practice is needed to confirm this. In addition, is also unclear how inexperienced individuals respond to being located in a meta-stable region during practice. Therefore, to provide an empirical basis for using meta-stability as a rationale underpinning learning intervention I proposed an experiment that observed the practice of a group of experienced and a group of inexperienced climbers under meta-stable task conditions and also, the transfer of their performance (Chapter 5).

I conducted an analysis of each individual's performance and exploratory behaviour. The amount and rate at which learning occurred was shown to interact with the amount of climbing experience reported by the participants. More experienced climbers transferred learning that was induced under the meta-stable condition. Inexperienced climbers were also induced to learn on a route that required use of an advance climbing action and the meta-stable route. Under transfer, the individuals in the inexperienced group who showed more exploration performed best. Hence, good support is provided for utilising meta-stability for facilitating individuals to explore new or better performance parameters.

To what extent theoretical principles in simple movement models extend to physical activity contexts remains unclear and many studies that enhance task complexity have revealed many convincing examples where key perceptual-motor couplings can be disrupted. I therefore first determined how prior experiences influence the behavioural tendencies of individuals (Chapter 6, Experiment 1). It was found that the coordination tendencies transfer to the indoor climbing. However the transfer of coordination tendencies was not shown to interfere with performance, suggesting that a variety of different ways of undertaking a climbing task is possible, and may allow individuals to use these existing coordination tendencies as a basis from which to learn new skills. I therefore developed a method to evaluate the ability of beginners to use different climbing patterns of coordination to determine their relative levels of stability (Chapter 6, Experiment 2). I did this by adapting a scanning procedure, which required participants to attempt to use different patterns of climbing coordination. The results showed whilst advanced climbers are able to effectively modify mobility with more complex behaviour (climbing side on the wall), beginners are unable to do so, their smoothness suffering as a consequence. In this respect, although the beginners could use the side-wall pattern, they were unable to use the pattern effectively or smoothly. A pre- and post-test intervention design then used the scanning procedure and transfer tests to show the effect of practice on the emergence of different climbing patterns of coordination in a group of beginners (Chapter 6, Experiment 3). A group of beginners were shown to transition toward advanced styles of climbing and performance on a transfer test revealed comparable levels of performance to a more experienced group. This study showed that extensive practice under meta-stable task design can lead to behaviour similar to experienced climbers, however the same degree of flexibility was not evident. Additionally, it was found that the learning dynamics were individually specific. Whilst globally, performance improvement followed a linear function, some individuals showed a linear improvement whilst other showed evidence of an abrupt transition.

Table 7.2 summarises the key findings from the thesis and highlights how the contents of the thesis answered the five research questions.

Table 7-2. Research questions addressed by the thesis.

Research Question One: What models and frameworks explain the acquisition of new skill in complex/emergent physical activity contexts? And, what are the research priorities in this field?
• In Chapter 2 I integrated key ideas in ecological psychology and dynamical systems theory to provide a basis for understanding movement variability with respect to its functional

properties. I also considered emerging and future research directions in skill acquisition in sport and physical activity settings.

- Functional movement variability in complex multi-articular tasks is indicated by qualitative changes in movement patterns, co-adaptation amongst different components of the movement system, and exploratory behaviour.
- Novel skill learning involves exploratory behaviour that can be facilitated through constraints manipulation that allow individuals to use existing skills: the adaptation of existing skills is one reason that Individuals, faced with the same learning task, differ in the rate and nature of learning.
- Whilst in simple tasks, destabilization of pre-existing skills and reorganisation of the entire repertoire have been demonstrated, the nature of learning in complex multi-articular physical activity contexts in poorly understood.
- High priority should be given to research that can sample performance, learning and its transfer under constraints representative of the complex environments that individuals normally participate and with an active community of experts. In this way implementation strategies can be defensibly implemented.

Research Question Two:

What research vehicle and measurement strategies are viable to investigate the acquisition and transfer of complex multi-articular skill?

- In Chapters 3 & 4, I outlines the results of a systematic review of research pertaining to coordination and it's acquisition in climbing tasks to determine how skill in the activity could be understood.
- Skilled climbing performance can be characterised by smoothness (such as organisation of actions around a minimisation of jerk) and fluency (optimal linking of sub-movements in the spatial and temporal dimensions) in whole body dynamics and hand-hold reaction forces.

- Perceptual and movement adaptations, including gaze behaviour, limb activity and postural adjustment, appear to be optimised in elite individuals to support smoothness and fluency of action during climbing.
- Behavioural measures including exploratory and performatory behaviour provide an estimate of individual climber intentions.
- Fluency measures, capturing spatial and temporal performance dimensions can, when integrated with performatory and exploratory measures, reveal insights into previously contradictory results, indicating reasons why certain actions might reduce fluidity and yet be support goal achievement.
- Fluent ascent and related behavioural adaptations, should in principle, be the most efficient when optimized by the individual: a key hypotheses developed is that adaptations supporting fluent climbing behaviour during an ascent are more conducive to successfully climbing a route.

Research Question Three:

Do data acquired in using the research vehicle support the theoretical framework adopted?

- In Chapter 5 and 6 I conducted an intervention studies to determine the impact of practice under different conditions attempting to facilitate different coordination regimes including meta-stability.
- Independent of skill level, meta-stability in practice design was shown to support learning.
- The amount and rate at which learning occurred in a complex multi-articular climbing task was shown to be dependent on the existing skill levels of the climbers.
- Skill was shown to moderate the exploration of affordances where lower skill level involved greater exploratory actions.
- The transfer of skill was shown to be supported by practice effects induced under meta-stable practice conditions in experienced individuals.

- The successful transfer of skill in inexperienced individuals was supported by exploratory behaviours during performance. That is, during transfer, inexperienced climbers showed higher levels of exploratory actions and lower levels of entropy, whereas at the beginning of practice high exploration and high entropy was observed.
- Non-specific climbing experience significantly influences the types of climbing actions spontaneously used in an indoor climbing task.
- Experienced climbers modify both mobility and movement complexity to maintain smoothness of hip trajectory during climbing.
- Side orientated body-wall coordination states during dynamic movement requires climbing specific experience, whereas, face-wall coordination states can be dynamically used without prior climbing specific experience.
- After 7 weeks of practice, beginners were shown to spontaneously acquire new side orientated body-wall coordination states and achieve similar levels of skill transfer as experienced climbers. However, beginners did not learn to modify both mobility and movement complexity to maintain smoothness of hip trajectory in a scanning procedure.
- Individuals who are in the early stages of learning in a complex multi-articular climbing task show different learning profiles in the evolution of performance outcomes, including, linear improvement and abrupt transitions.

Research Question Four:

What strategies can be developed to improve skill acquisition in physical activity settings?

- In physical activity settings that involve a mixture of self-paced locomotion and discrete behaviours behavioural flexibility can enhance performance.
- Perceptual and motor adaptations that increase measures of smoothness and fluency during climbing tasks are related to a higher climbing ability level.
- Practitioners can interpret existing skills as a basis from which individuals can learn new

skills. Constraints can be designed to facilitate the exploitation of these existing skills.

- Individual vary in learning dynamics, sometimes demonstrating abrupt transition in performance and sometimes a gradual, more linear improvement.
- Meta-stability represented in practice design, supports the general improvement in performance and the emergence of new skills.
- Rather than be considered as error, movement variability should also be evaluated in how it can be functional to enhance performance in complex multi-articular skills, in particular the coaches should interpret exploratory behaviour as an indicator of learning.

7.2 Emergence of skill in climbing

Climbing requires an individual to adapt to a more or less vertical and ever changing structure of a climbing surface with the task goal of completing a route without falling (Orth, Davids, & Seifert, 2015). Skilled behaviour in climbing is predicated on how an individual dynamically adapts actions to varied climbing surface properties (variations in shape, texture and relative distancing of features, Davids, Brymer, Seifert, & Orth, 2014). Due to the extreme postural constraints imposed by the small protrusive/sunken edges embedded into a sloped surface, climbers need to continuously regulate their use of the environment relative to their internal state during performance. For example, muscular fatigue reduces the ability to produce required friction force at the finger-tips (Vigouroux & Quaine, 2006) and can be intensified if an individual becomes 'blocked' (i.e., cannot perceive how to use holds to continue climbing, White & Olsen, 2010), uses inefficient movements (de Geus, O'Driscoll, & Meeusen, 2006), or, does not perceive and exploit opportunities to rest (Fryer et al., 2012). Hence, improving climbing skill, in tasks requiring route finding (such as bouldering, sport and traditional climbing), can be facilitated by helping learners to detect and use relevant information sources during climbing to support successful performance and energy efficient actions (Orth et al., 2015).

In emergence of skilled behaviour inclimbing, three time-scales of change (slow, moderate and fast) appear to exist. According to Cordier et al. (1993), 'fast' variables account for the dynamics of motor *performance*. Changes in the fast timescale, typically expressed in seconds, are observed as the temporary (re)organization of behaviours in a discrete performance trial. 'Moderately fast' variables, account for *learning*, refer to the relatively persistent adaptation of the individual to the environment, in a timescale perhaps expressed over several hours (Cordier, Mendès-France, Bolon, & Pailhous, 1993). Effects of learning can be observed over many performance repetitions (referred to as learning dynamics) and under retention and transfer conditions (Davids, Button, & Bennett, 2008). Finally, Cordier et al. (1993), defined 'slow' variables to account for the dynamics underlying the emergence of highly skilled behaviours. This timescale may be expressed across many months or years, and, can be reflected in the structural/functional adaptations developed through progressive training (e.g., Bläsing, Güldenpenning, Koester, & Schack, 2014; Vigouroux & Quaine, 2006).

7.3 The effect of skill on the rate and level of learning in climbing

In a series of innovative studies, Cordier and colleagues (Cordier, Dietrich, & Pailhous, 1996; Cordier et al., 1993; Cordier, Mendès-France, Bolon, & Pailhous, 1994; Cordier, Mendès-France, Pailhous, & Bolon, 1994) evaluated effects of practice during ten trials on the same route (set at a French Rating Scale of difficulty [F-RSD] of 6a). Skill level effects were assessed by contrasting performance of an advanced group (F-RSD between 7a-7b), with an intermediate group (F-RSD between 6b-6c). Each climber's position on the wall was analyzed by digitizing the movement of a light-emitting diode (LED), attached to the back at the waist, and video recorded with a camera during climbing. Digitized trajectories were projected onto the climbing wall plane, and spatial and temporal characteristics of performance were analysed. From the positional data several variables were calculated to characterize overall stability including: the geometric index of entropy (Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994); spectral (Cordier et al., 1996); fractal (Cordier et al., 1993); harmonic (Cordier et al., 1996), and; phase portrait analyses (Cordier et al., 1996).

Cordier and colleagues showed how the existing skill level of learners affected their subsequent level and rate of performance improvement. Figure 7-1 summarises the results of analyses undertaken by Cordier et al. (1993), displaying skill differences (Figure 7-1 Panels A, B and C); learning rates (Figure 7-1 Panels A, B and D), and level of learning (reflected in magnitude of change over 10 trials, Figure 7-1 Panel E). The advanced group (Panel A) reached a stable state (a plateau in the rate of improvement) earlier (indentified at Trial 3 in Cordier et al., 1993) than the intermediate group (Panel B) (identified at Trial 8 in Cordier et al., 1993). Both groups achieved a similar level of performance in terms of movement efficiency (captured by geometric index entropy) by the tenth trial of practice (see Figure 7-1, Panel E).

Cordier et al., (1996) emphasized that the advanced group typically used regular lifting movements (every 3 seconds on average), whereas the intermediate group showed no clear tendency for displacements to recur at any particular frequency. Furthermore, phase portrait analyses of each group revealed that advanced individuals displayed more regular movement characteristics (stable dynamics), whereas, intermediate climbers exhibited less predictable dynamics. These findings suggested how advanced climbers achieve a stable ‘coupling’ between their repertoires of existing capabilities and changing environmental features (changing as function of the climbers' movements). In contrast, the relative difficulty of the route for the intermediate climbers, meant that these less skilled individuals were less ‘coupled’ to the climbing surface throughout practice (Cordier et al., 1996, pp., p. 805). The more sensitive temporal movement analyses placed into perspective the large learning effect along the spatial dimension shown by the intermediate climbers who achieved similar levels of movement efficiency (as indexed by entropy) relative to the advanced group (refer to Figure 7-1, Panel E), but, still required practice to improve efficient temporal dynamics.

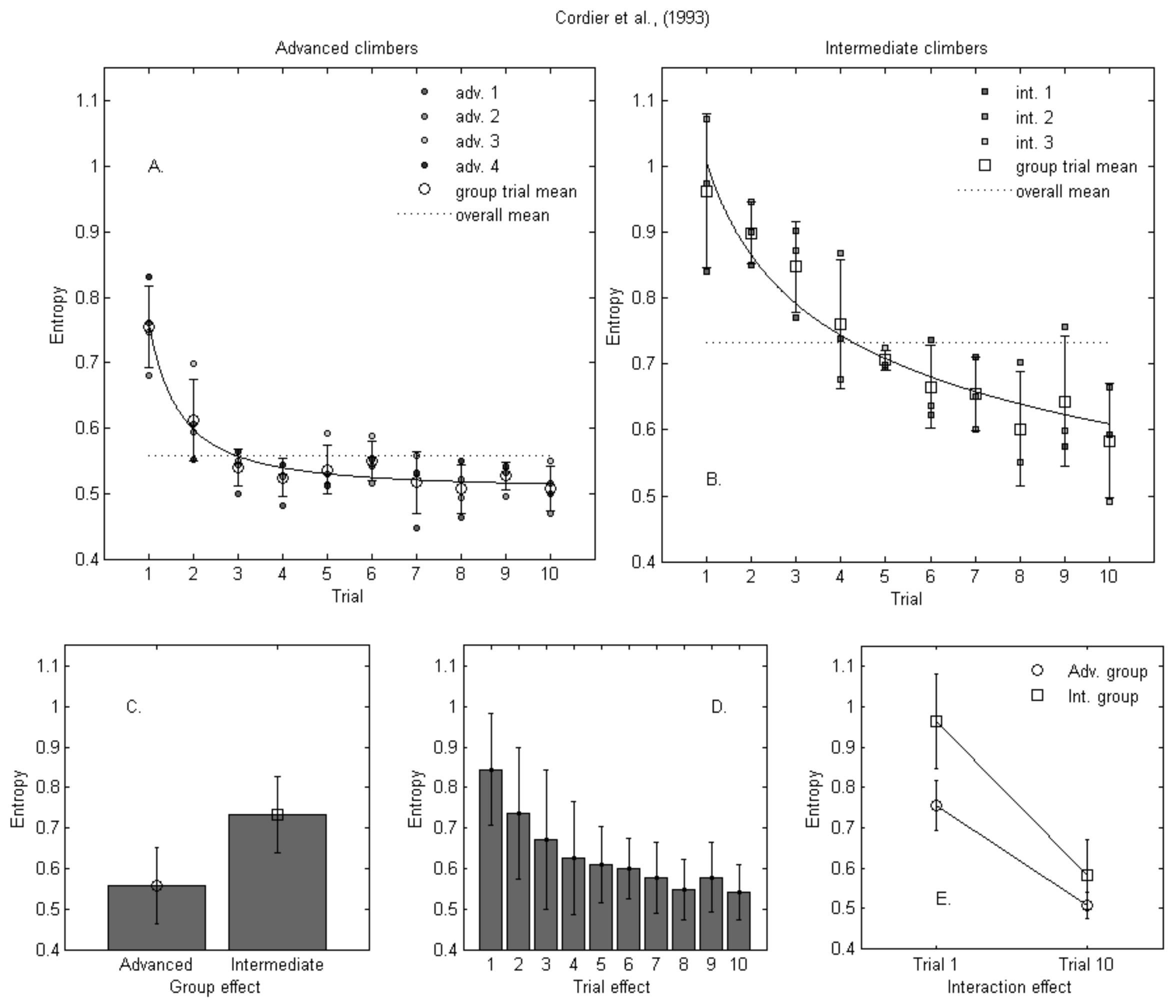

Figure 7-1. Data adapted from Cordier et al. (1993, p. 373) showing practice and skill effects as indexed by entropy of the hip trajectory when climbing the same route over ten trials. **Int.** = Intermediate climber, **Adv.** = Advanced climber. Error bars = ±1 standard deviation.

Practical implications of these findings suggests that, once an individual finds a globally effective route pathway, a key constraint on improving performance on a given practice route, should influence the temporal structuring of actions. For example, once an effective route path has been determined, a climber may further improve performance by linking movements in a more periodic fashion. For climbers where the gap between the route difficulty and their current ability is too easy, as was the case with the advanced group, the learning effect may be limited, with subsequent trial-to-trial dynamics likely to follow a power law function (such as discussed in, Guadagnoli & Lee, 2004; Newell, Mayer-Kress, Hong, & Liu, 2009). Emphasizing training at an easy relative difficulty may, therefore, be inefficient for progression of the individual's red-point (highest performance grade achieved with physical practice) or on-sight (highest performance without prior physical practice) ability level. On the other hand, for individuals learning on a route that is close to the limit of their ability level it may be expected that a learning effect can continue to be meaningful over multiple days of practice. Indeed, these conclusions are well supported by the data presented in Chapter 5 Study 1, and Chapter 6 Study 3.

7.4 The role of perception-action coupling and climbing affordances in learning

Perception-action coupling refers to the patterned relationships that are formed between human movements and perceived information in a performance environment. It is a concept that underpins the design of practice contexts (Handford, Davids, Bennett, & Button, 1997). The suggestion is that internal and external sources of information can be detected by the individual's sensory system and perceived directly providing affordances for action. Affordances are defined as opportunities for action in a performance environment with reference to a particular individual (Gibson, 1979). A major difference between individuals of varying experience levels is in the information attended to, and, therefore, the possible opportunities (affordances) available to be utilised.

The relationship between skill and affordance perception was examined in detail by Boschker et al. (2002). One experiment involved three groups of climbers: an advanced group (F-RSD from 7a to 7c+), a lower grade/intermediate group (F-RSD from 4c to 5c), and an inexperienced group (no climbing experience whatsoever). Participants were required to visually inspect a route of 23 holds (set between 5c to 6a F-RSD) for a defined period of time, and the task goal was to recall the position and orientation of the holds needed to complete the route. In the first trial, an inspection period of

2.5 minutes was given, on subsequent trials participants were then given a 5 second view period. The average accuracy group values for successive trials are shown in Figure 7-2, Panel A (see also Boschker et al., 2002, p. 29). In another experiment, an inexperienced group and an advanced group undertook the same recall task as the first experiment, but, participants were instructed to 'think aloud during the reproduction task, verbally reporting everything they thought about, especially what was perceived when looking at the climbing wall and why they reproduced the holds in the way they did' (Boschker 2002, p. 32). Verbal reports were divided into statements referring to 'structural features' or 'climbing opportunities' (for details refer to Boschker et al., 2002, pp. 32-33). See Figure 7-2, Panels B and C.

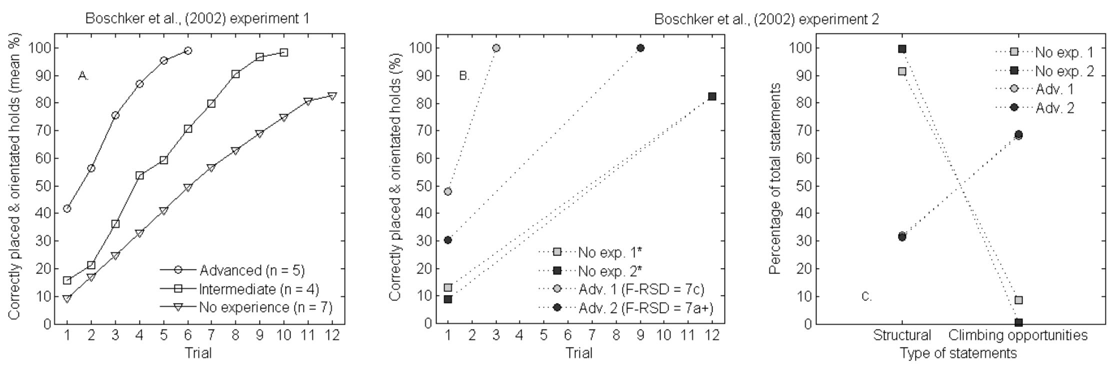

Figure 7-2. Recall performance and verbal reports during a route recall task reported in Boschker et al., (2002). The task involved a climbing route set between 5c to 6a F-RSD. Participants repeatedly attempted to reconstruct the route until it was fully and accurately reproduced or until the end of Trial 12. **Adv.** = advanced climber, **No exp.** = no experience in climbing, **F-RSD** = French rating scale of difficulty. ***** = actual values at Trial 12 were not reported, Trial 12 data for both inexperienced climbers in Panel B is instead taken from the estimated mean percentage of the no experienced group at Trial 12 from Experiment 1.

These results of Boschker et al. (2002) showed that the advanced climbers had more accurate recall than both intermediate and less experienced climbers after 2.5 minutes of preview (Figure 7-2, Panel A, Trial 1 data). Additionally, general experience in climbing tasks supported a higher rate of recall over repeated trials (Figure 7-2, Panel A & B). According to Boschker et al. (2002) the same mechanism underpinned superior Trial 1 performance and superior trial-by-trial performance. They proposed that individuals had picked up ‘clustered’[1] information if they recalled more than nine items after the 5 second viewing period, thus exceeding short-term memory capacity (but see, Wagman & Morgan, 2010). Specifically, to overcome inherent limitations on short-term memory, climbers must use different types of information allowing them to draw on experience (i.e., long-term memory) rather than storing more information in short-term memory.

In climbing, information can be nested in the form of climbing opportunities that reflect the functional properties of holds, which refer to their reachability, graspability, and stand on-ability, as well as opportunities for specific climbing moves (Boschker et al., 2002). For example, various climbing techniques require specific bodily configurations with respect to orientation and relative positions of numerous holds (Seifert et al., 2015). This allows multiple holds to be collectively perceived as a single, nested, climbing opportunity (Boschker et al., 2002, p. 31). Data reported in Experiment 2 (Figure 7-2, Panels B & C) support this contention, indicating that, as individuals gain climbing experience, they perceive affordances that hold properties present (i.e., functional properties). Inexperienced individuals almost exclusively attend to structural details of a surface (Figure 7-2, Panel C, see also Seifert, Wattebled, et al., 2014). This invites speculation, that, should climbers perceive movements in series (as nesting of climbing actions in sequence), this skill might facilitate recall of more holds and may be one of the reasons recall performance increases with skill level (Boschker et al., 2002).

Practically, these findings imply that skilled behaviour is underpinned by perception of affordances that support effective and efficient climbing. An individual’s attention during practice of a climbing route should, therefore, be guided toward the functional properties of the climbing surface that

[1] The term ‘nested’ is preferred here because the term ‘clustered’ implies that only spatial information has been perceived, thus, does not effectively capture the possibility that perceiving affordances also includes temporal properties.

support skilled behaviour. Understanding what prevent holds from being perceived as climbing opportunities may help improve skilled affordance perception. Fundamentally, this would emphasize designing route properties (such as the architecture of holds or wall slope) during training based on the individual's unalterable (such as anthropometrics) and trainable capabilities (such as strength) in order to ensure that climbing actions are within physical capabilities. Indeed, even inexperienced climbers can perform recall tasks at the same level as advanced climbers as long as the route is within their current climbing ability, whilst, advanced climbers lose their recall performance advantage over inexperienced climbers when tested on an 'impossible to climb' route (Pezzulo et al., 2010). Following this line of reasoning, interventions that improve action capabilities, such as finger and hand grip strength and endurance (Vigouroux & Quaine, 2006), or, upper-limb power and endurance (Laffaye, Collin, Levernier, & Padulo, 2014), may support training transfer (such as climbing unfamiliar routes in competition) on the basis of the behavioural opportunities made available this way. Indeed, this expectation suggests that certain exercises can enable positive transfer based on motor system adaptation, however, these expectations are not always reasonable, particularly in more advanced individuals (Issurin, 2013).

7.5 Improving skilled perception of affordances though constraints manipulations

Temporary constraints manipulation can be used to affect affordance perception and potentially lead to meaningful qualitative changes in behaviour. According to Gibson (1979; Seifert, Orth, et al., 2014), "The observer may or may not perceive or attend to the affordance, according to their needs, but the affordance, being invariant, is always there to be perceived" (cited in, Pijpers, Oudejans, & Bakker, 2007, p. 108). Pijpers et al., (2007) argued, that, since an environment can contain many affordances (e.g., a hold can be grasped in different ways) many factors, such as an individual's internal states, influences their selection. Design factors such as climbing height (Pijpers, Oudejans, Bakker, & Beek, 2006) or top-rope vs. leading conditions (Hardy & Hutchinson, 2007), reflect environmental and task constraints that do not change the available affordances, but, that can interact with an individual's intentions, changing affordance perception based on altered needs. For example increased anxiety may lead an individual to focus intentions toward remaining fixed to a surface, with attention directed toward perceiving affordances that support stability. This can be observed in behaviors like reduced distance between grasped holds or a more proximal (closer to the body) attentional focus (Pijpers et al., 2006).

Figure 7-3 represents an integration of the concepts raised throughout this thesis, placing into perspective the evolution of learning with respect to factors that affect skilled affordance perception. The model makes initial assumptions that affordance perception is qualitatively distinct based on actions supported, and, that skilled affordance perception correlates with skilled climbing. Early in learning, fundamental affordance perception supports baseline needs such as avoiding falling. With more advanced performers, or through practice, affordances are perceived in terms of improving performance, such as periodically chaining movements. The model in Figure 7-3 is layered into concentric circles to indicate how affordances are nested atop relative to each other where the perception of more advanced affordances entails the, perhaps, implicit perception of fundamental concerns. For example, perceiving hold usability can support remaining fixed to a surface although this may not be the intention of an individual, which may be instead be efficient progression. The model also indicates that beginners can perceive skilled affordances, as a function of relative route difficulty. For example a beginner inspecting a route with numerous and very large easy to grasp holds can still perceive hold usability. However, as task difficulty increases (e.g. holds get smaller), a beginner’s action capabilities may require their needs to shift towards affordances for seeking out characteristics of holds that support stability.

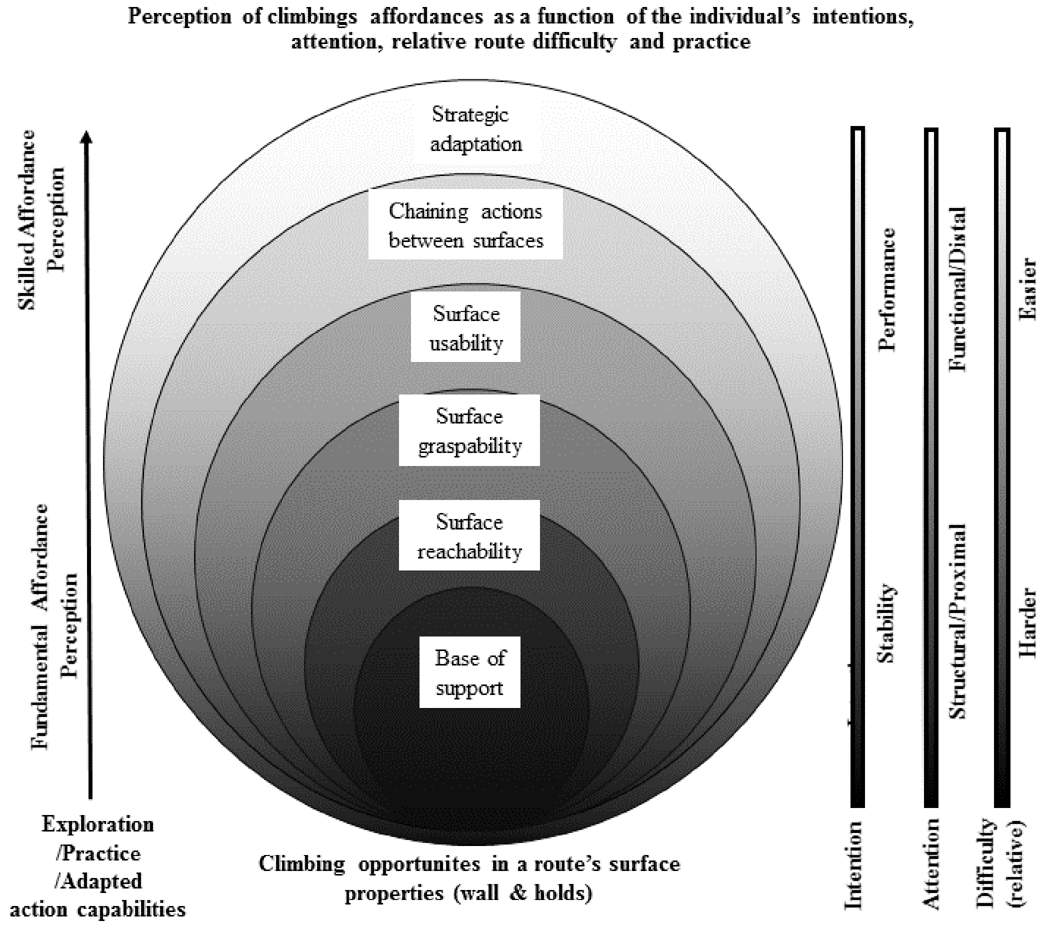

Figure 7-3. Affordance perception and skill in climbing.

7.6 Implementation: Effect of constraints manipulation on learning dynamics and the transfer of skill in climbing

Learning design is based on the structuring of practice and provision of learning opportunities by managing interactions at the level of the individual learner and their training constraints (Renshaw, Chow, Davids, & Hammond, 2010). Practically, simple constraints manipulation, such as providing instructions (Boschker et al., 2002) or modifying hand hold properties (Orth, Davids, & Seifert, 2014) can directly impact upon whether climbing affordances are utilised. Thus, effective learning design involves managing the interaction between constraints that facilitate progression toward skilled affordance perception during training. In this final section, a learning intervention undertaking in thesis is used to exemplify a specific training problem.

Orth et al. (2014) assessed the impact of practice under three different conditions on climbing entropy. Routes were designed assuming that participants would use pre-existing experience to perceive affordances for supporting efficient traversal. Six individuals (with a self-reported red-point F-RSD = 6a) were observed over four separate days practising on three routes. On each day, participants climbed the three routes once each in counterbalanced order. Routes were each set at 5c F-RSD, but, were different in terms of hand-hold orientation set into each route, including: hand-holds with horizontally aligned edges graspable with the knuckles running parallel to the ground; hand-holds with vertically aligned edges graspable with the knuckles running perpendicular to the ground; and hand-holds with both a horizontally aligned edge and a vertically aligned edge. The double-edged route was designed to allow climbers to explore a variety of grasping actions by presenting a choice at each hold. A transfer test was also included using a combination of the hold types from the three different learning conditions (see Figure 7-4).

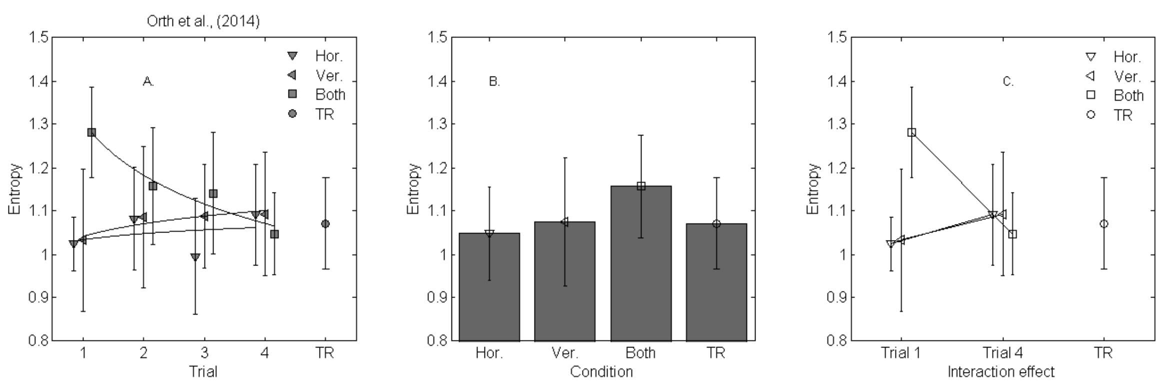

Figure 7-4. Data adapted from Orth et al., (2014). **Hor.** = horizontal-edge condition, **TR** = transfer, **Ver.** = vertical.

Data suggested that experienced climbers only displayed a learning effect on the double-edged route (Figure 7-4). Additionally, positive transfer can be inferred from the clear difference between Trial 1 (on-sight) on the double-edged route and the on-sight transfer test performance. Implications of these findings are two-fold. First, in experienced climbers, an existing platform of expertise can support rapid adaptation to a route, even if unfamiliar. On the other hand, introduction of choice into handhold properties, affords adaptation and problem solving at the level of route finding. Orth et al. (2014) suggested that successful transfer was induced because of the experience of climbers on the double-edged route. Specifically, the capacity to use existing experience to adapt rapidly to the multiple hold choices found in the new climbing route underpinned the positive transfer of skill. In a follow up study, Seifert et al. (2015) used the same experimental procedure as Orth et al. (2014), but, considered potential mechanisms underpinning positive transfer by assessing the number of exploratory actions in relationship to entropy. A key finding was, that, whilst Trial 1 conditions showed both high levels of entropy and exploratory behaviour, on the transfer test, more efficient performance was associated with higher amounts of exploratory behaviour. According to Seifert et al. (2015), these findings indicated that climbers can learn to explore efficiently. Thus, a potential behavioural mechanism underpinning positive transfer might be effective exploratory behaviours.

Practically speaking, any on-sight climb might be conceptualized as a skill transfer problem, requiring adaptations during performance with unfamiliar surface properties and in contexts with dynamic environments (such as outdoors). Assuming positive transfer is supported by skilled affordance perception, helping individuals to explore and learn how to find information specifying efficient climbing opportunities, is one approach that might improve on-sight climbing ability. Similarly, motor adaptions, such as improving a beginners ability to explore balance for longer periods of time, are likely to assist with the transfer of skill or learning (improved rate of learning in new contexts due to experience), because, motor adaptations can support longer periods of remaining in contact with holds.

7.7 Future research and perspective: The role of exploratory behaviour in understanding the relationship between learning and affordances

Many of the ideas discussed throughout this thesis have implied that exploration during practice is a potential mechanism that can help learners to improve performance over time. In climbing, exploratory behaviour has been observed with respect to qualitatively different climbing affordances (see Table 7-2). For example, exploratory behaviours related to functional properties of holds can reveal opportunities for movement at the hips without subsequent displacement (Boulanger, Seifert, Hérault, & Coeurjolly, 2015). Exploration in postural regulation during periods of immobility suggest that prolonged pauses during climbing may still be useful to the learner. Postural exploration seems particularly relevant for beginners considering this may allow the individual to determine more efficient positions and new body-wall orientations that may be important for more advanced movements. On the other hand, the more advanced individual may benefit from immobility for different reasons. For example one possibility is that static states can afford resting and recovery and should be distinguished from exploration as a performatory behaviour (Fryer et al., 2012). Another possibility is that the individual may benefit from immobility by visually exploring upcoming holds, perhaps indicated by the amount of fixations made and their relative distance to the individual during immobility (Sanchez, Lambert, Jones, & Llewellyn, 2012).

Another form of exploration includes reaching to touch a hold but not grasping it or using it to support the body weight (Seifert et al., 2015). This form of exploration is believed important for achieving an accurate body-scaling to the environment (Pijpers et al., 2007) and, perhaps, as different techniques, such as dynamic moves, become part of an individual's action capabilities this boundary of reachability may distinguish individuals of different abilities. Making adjustments in how a hold is grasped prior to using it to support displacement is also a form of exploration perhaps in terms of graspability or usability. For example, prior to applying force to a hold climbers can be seen, in some cases, to make adjustments to how they position their hand on a hold. Such exploratory behaviour may be important to improve the amount of friction that can be applied to the hold (Fuss, Weizman, Burr, & Niegl, 2013), or, enable a qualitatively different way of using the hold such as in cases where multiple edge orientations are available (Seifert, Orth, et al., 2014).

It has also been speculated that exploration can support perception of opportunities for new climbing moves (Seifert, Orth, Herault, & Davids, 2013). This may be observed by examining how climbing actions are different over practice. For example, from one trial to the next, different route pathways, body orientations or grasping patterns might be used, reflecting exploration emerging during the dynamics of learning. Thus, during intervention the nature of learning behaviour may be better understood by evaluating the level at which exploration emerges. A substantial challenge, therefore, for future of learning research in climbing is in measuring exploration at different levels of analysis with respect to performance, both, in technically manageable and theoretically consistent ways.

Table 7-3. Specific forms of exploration directed toward qualitatively distinct affordances.

Affordance layer	Movement pattern	Intention	Information foci	Example
Base of Support	'X' shaped, COM immobile	Maintain contact with the surface	Holds for hands and feet	Seifert et al., (2011)
Surface Reachability	Touching not grasping, COM immobile	Explore reachability	Individual-surface distance	Pijpers et al., (2006)
Surface Graspability	Gasping actions without subsequent usage, COM immobile	Explore graspability	Surface geometric properties (structure)	Fuss et al., (2013)
Surface Usability	Performatory actions with progression, COM mobile	Use surfaces to prepare or achieve route progression	Movement opportunities (function)	Boschker et al., (2002)
Chaining	Spatial-temporal efficiency of linked actions	Use upcoming surface to regulate current positioning	Distant surfaces, movements in series	Cordier et al., (1993)
Strategic adaptations	Within route active recovery/exploration	Use of surfaces to rest or plan	Distant surfaces, internal state	Fryer et al., (2012); Sanchez et al., (2012)

7.8 Conclusions

Skill acquisition in climbing can be understood through temporary interactions between the individual learner and the performance environment throughout practice. Pedagogical practice in climbing should focus on helping individuals to skillfully interact with climbing environments, where, even inexperienced individuals bring to the task a unique set of adaptations that can form the basis from which to design a learning environment. Such a learning process entails a progression in the individual's capacity to efficiently adapt to new climbing routes, a process facilitated by skilled affordance perception.

7.9 Practical implications summary

- Observing performance over repeated trials of practice allows the evolution toward skilled behaviour to be assessed. Additionally, through pre- and post-test measures of performance, and testing the transfer of skill and learning, the relative importance of an intervention can be interpreted.
- The transition toward skilled behaviour involves developing exploratory behaviour across different levels (i.e., hands/feet, limb and hip orientations), which support each learner's current needs (such as stability or improved performance).
- The practitioner can influence affordance perception though manipulating constraints during training to influence each individual's intentions, needs and action capabilities. For example, a task or environment can be modified to encourage the individual to actively explore.

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CHAPTER 8. CONCLUSIONS

Important determinants of ongoing participation in physical activity are skill level and task experience. Research is needed to evaluate learning behaviour in the sorts of complex performance environments that individuals normally participate. This thesis evaluates key theoretical mechanisms for acquiring skill, using climbing as the research vehicle.

The thesis aimed to determine how environment-performance relationships (specifically practice contexts that promote exploration of different coordinated behaviours) support the acquisition of multi-articular skill (the ability to improve performance in the practice context) and then, determine what mechanisms support improved transfer of skill (improved performance or learning under conditions different to practice). The programme of work addressed by this thesis was: (1) What frameworks explain the acquisition of skill in complex, emergent physical activity contexts? And, what are the research priorities in this field? (2) What research vehicle and measurement strategies are viable to investigate the acquisition of complex multi-articular skill? (3) Do data acquired in physical activity contexts support the theoretical framework adopted? (4) How can mechanisms used to explain learning new skills be evaluated? (5) What strategies can be developed to improve skill acquisition in physical activity settings?

Through literature review I establish a perspective on how skilled behaviour can be conceptualized as an emergent property that involves constrained exploration of a movement system's available degrees of freedom (i.e. the multiple linkages, joints and muscles). Two theoretical themes emerged in relation to the design of research tasks and learning. First, referred to as representative task design, it was found that the greater extent to which a task simulates properties of complex performance contexts, the more behavioural variability that is functional for goal achievement emerges. Second, referred to as meta-stable behaviour, when required to perform under conditions that support multiple actions individuals spontaneously explore a greater variety of qualitatively different patterns of behaviour. In each case, representative design and meta-stability appear to support spontaneous exploratory behaviour, which, is considered a key indication that an individual is learning. Further research is needed to strengthen current theoretical frameworks by considering links between representative design, meta-stability and functional movement variability with respect to behaviour during learning and under transfer conditions. I propose therefore, that high research priorities should be placed on sampling motor learning and transfer processes in the sorts of contexts corresponding to those that individuals actively participate.

Most previous motor learning studies involving complex multi-articular tasks have been designed to test movement coordination in discrete interceptive tasks or in cyclical continuous tasks. However, participation in physical activity pertains to tasks that nest cyclical locomotor behaviour with a rich mixture of potential discrete behaviours. Hence, a research vehicle where individuals use both locomotion and discrete behaviours would be of considerable research value. I therefore proposed the physical activity of climbing to provide a new research vehicle to address the current research priorities. I undertook a much needed systematic review of the literature examining in detail the impact of skill, practice and manipulation of constraints (interactions between task, environmental and individual factors) on coordination of action during climbing activities. Further research is needed to understand the impact of different intervention conditions on learning and to evaluate individuals with different levels of experience to determine what skills require climbing specific experience.

The previous studies showing meta-stability in complex multi-articular tasks have used experienced individuals as participants and have not reported trial effects. If, as predicted, learning is induced in experienced individuals under constraints that induce meta-stability, observation of behaviour over repeated trials of practice is needed to confirm this. Furthermore, if learning effects are to be attributed to meta-stable practice design, multiple conditions need to be evaluated and with respect to a transfer test. It is also unclear how inexperienced individuals respond to being located in a meta-stable region of performance during practice. To establish future research directions, I observed the practice of a group of experienced and a group of inexperienced climbers under meta-stable task conditions and also, the transfer of their skill after practice. I conducted an analysis of their exploratory behaviour at the hip and hand levels using a semi-automatic tracking procedure combined with manual annotations. This study showed that learning emerged at different levels, the hands and body. The amount and rate at which learning occurred was shown to interact with the self-reported ability level of the participants. Climbers with more experience were induced to learn only under the meta-stable condition. The less experienced climbers were induced to learn on a route that required use of an advance climbing action in addition to the meta-stable route. Under transfer, and quite contrary to expectations, the individuals in the less experienced group who showed more exploration demonstrated better performance.

Individuals exhibit stable patterns of movement coordination that can cause resistance or inhibition to behaviour more functional to new performance constraints. Scanning procedures determine the stability of existing movement coordination by requiring that the individual attempt to use a range of coordination patterns. To understand the effect of existing skill on behaviour under conditions that induce meta-stability, I designed a series of experiments that required beginners and experienced climbers to adopt different patterns of climbing coordination. In these experiments I applied automatic tracking of hip position using a basic Kalman filter. Time series data of worn sensors attached to at the hip and limbs enabled the assessment of body-wall coordination patterns and activity states. Finally, grasping orientation was assessed using manual video annotation. The results showed significant effects of prior experience and which climbing patterns were stable. Individuals without indoor climbing experience tend to grasp holds using simple techniques whereas experienced climbers use a greater mixture of grasping actions. It was also found that inexperienced individuals were able to climb using what was considered an advanced body-wall coordination pattern however, were significantly less smooth compared to the experienced climbers. Interestingly, individuals who fell during the scanning procedure, were unable to use the advanced body-wall coordination pattern when moving. An intervention study involving practice under conditions that support meta-stability, was then undertaken on individuals who were unable to use the advanced body-wall coordination pattern when moving. It confirmed that prolonged exposure to a meta-stable task can lead to the acquisition of behaviour that is representative of skills that experienced indoor climbers' exhibit. A pre-and post-test intervention design used a scanning procedure to show the emergence of advanced body-wall coordination patterns. A transfer test also revealed comparable levels of performance to that of a more experienced group of climbers.

The research evidence in this thesis suggests that in complex multi-articular skills, exploration is a key mechanism for acquiring new skills and can support fluent performance under transfer conditions. These data suggest that representing meta-stability in practice constraints supports the capacity to adapt performance to the inherent variability found in many physical activity settings such as the climbing domain. I discuss the impact of these ideas through practical strategies in how route design (such as hold orientation and grasp-ability) can be used to establish representative practice tasks for acquiring climbing skill.

In summary, this thesis adds to the small, but, growing body of literature to have investigated the impact of training interventions on the transfer of skill and primarily improves our understanding of how constraints influence the individual-environment relationship during practice. Although the research is limited to a sample of individuals in upper Normandy, France, the methods developed in this thesis will be useful to other researchers studying individual-environment relationships in complex multi-articular tasks. The results can also be of interest to applied practice for informing the design of learning contexts that support the acquisition of transferable skill.

Appendix A. Communication & Invited Seminars

Oral Communications & Conferences

Orth, **D**., Kerr, G., Davids. K., Seifert, L. A scanning procedure applied to climbing: An ecological dynamics approach. Paper presented at the, *1st Scientific Conference on Motor Skill Acquisition*. Finland, Kisakallio, 2015.
Orth, D., Davids, K., Seifert, L. Hold design supports learning and transfer of climbing fluency. Paper presented at the, *2nd International Rock Climbing Research Congress*. Pontresina, Switzerland, 2014.
Orth, D., Seifert, L., Button, C., Davids, K. Representative learning design in climbing. Paper presented at the, *4th International Conference on Complex Systems and Applications*. France, Le Havre, 2014.
Boulanger, J., Seifert, L., Dovgalecs, V., Herault, R., **Orth, D.** & Davids K. Automatic detection of climbing affordances. Paper presented at the, *4th International Conference on Complex Systems and Applications*. France, Le Havre, 2014.
Button, C., **Orth, D.**, Seifert, L. & Davids, K. How practice influences perceptions of difficulty and hold usability in indoor and outdoor climbing environments. In: Draper, N. (Ed.). *Congress of Sport and Exercise Science New Zealand. Christchurch*, New Zealand, 2013.
Orth, D., Davids, K., Hérault, R. & Seifert, L. Indices of behavioural complexity over repeated trials in a climbing task: Evaluating mechanisms underpinning emergence of skilled performance. Paper presented at the *European Conference on Complex Systems*. Barcelona, Spain, 2013.

Scientific Communications

Orth, D., Seifert, L., Hérault, R. & Davids, K. Metastability in perception and action in rock climbing. Poster presented at the, XVIIth International Conference on Perception and Action. Estoril, Portugal. 2013.
Orth, D., Davids, K. & Seifert, L. Perception and action during indoor climbing: Effects of skill level. Poster presented at the, *European College of Sport Science*, June 24-29th, 2013: Barcelona, Spain.
Orth, D., Davids, K., Herault, R. & Seifert, L. Dynamics of acquiring adaptive skills. Poster presented at the *Grands Reseaux de Researche, held at the University of Rouen*, Nov 29-30th, 2012: Rouen, France.

Invited Seminars

Orth, D. Visual-motor coordination in complex, self-paced tasks. *University of Rouen*, 18th March, 2015: Rouen, France.
Orth, D. Learning dynamics in climbing tasks. *University of Rouen*, 20th February, 2015: Rouen, France.
Orth, D., Davids, K., Kerr, G. & Seifert, L. Dynamics of acquiring adaptive skills in a complex multi-articular task. *Grands Reseaux de Recherche*, *held at the University of Rouen*, Jan 12th, 2015: Rouen, France.
Orth, D., Davids, K., Kerr, G. & Seifert, L. Dynamics of acquiring adaptive skills in a complex multi-articular task*. Queensland University of Technology*, 1st October, 2014: Brisbane, Australia.
Orth, D. & Seifert, L. Visual-motor skill in climbing. *University of Rouen*, 30th September, 2014: Rouen, France.
Orth, D., Davids, K., Kerr, G. & Seifert, L. Dynamics of acquiring adaptive skills in a complex multi-articular task. *Grands Reseaux de Recherche, held at the University of Le Havre*, 23rd January, 2014: Le Havre, France.
Orth, D., Davids, K., Kerr, G. & Seifert, L. Dynamics of acquiring adaptive skills in a complex multi-articular task. *University of Rouen*, 14th November, 2013: Rouen, France.

Appendix B. Publications

Orth, D., Davids, K., & Seifert, L. (2015). Coordination in climbing: Effect of skill, practice and constraints manipulation. *Sports Medicine*, First online, 1-14.
Seifert, L., Boulanger, J., **Orth, D.**, & Davids, K. (2015). Environmental design shapes perceptual-motor exploration, learning, and transfer in climbing. *Frontiers in Psychology,* 6, e1819, 1-15.
Orth, D., Davids, K., & Seifert, L. (2014). Hold design supports learning and transfer of climbing fluency. *Sports Technology*, 7(3-4), 159-165.
Seifert, L., Dovgalecs, V., Boulanger, J., **Orth, D.**, Hérault, R., & Davids, K. (2014). Full-body movement pattern recognition in climbing. *Sports Technology*, 7(3-4), 166-173.
Dovgalecs, V., Boulanger, J., **Orth, D.**, Hérault, R., Coeurjolly, F. J., Davids, K., & Seifert, L. (2014). Movement phase detection in climbing. *Sports Technology, 7*(3-4), 174-182.
Seifert, L., **Orth, D.**, Boulanger, J., Dovgalecs, V., Hérault, R., & Davids, K. (2014). Climbing skill and complexity of climbing wall design: Assessment of Jerk as a novel indicator of performance fluency. *Journal of Applied Biomechanics*, 30(5), 619-625.
Seifert, L., L'Hermette, M., Komar, J., **Orth, D.**, Mell, F., Merriaux, P., Pierre Merriaux, Pierre Grenet, Yanis Caritu, Romain Hérault, Vladislavs Dovgalecs, Davids, K. (2014). Pattern recognition in cyclic and discrete skills performance from inertial measurement units. *Procedia Engineering, 72*, 196-201.
Orth, D., Davids, K., Wheat, J., Seifert, L., Liukkonen, J., Jaakkola, T., Ashford, D., Kerr, G. (2013). The role of textured material in supporting perceptual-motor functions. *PLoS ONE*, 8(4), e60349, 1-14.

Papers in review

Orth, D., Davids, K., & Seifert, L. (2015). Constraints that represent a meta-stable regime support exploration during practice and the transfer of skill in a complex multi-articular task.
Orth, D., Kerr, G., Davids, K., & Seifert, L. (2015). Measures of efficiency and intentionality reveal skilled behaviours in climbers.
Seifert, L, Wattebled, L., **Orth, D.**, & Davids, K. (2015). Generality and specificity of skill transfer shape perception and action under varying environmental constraints.

Book chapters

Orth, D., Button, C., Davids, K., & Seifert, L. (2016). What current research tells us about skill acquisition in climbing. In L. Seifert, P. Wolf, & A. Schweizer (Eds.), *Science of climbing & mountaineering*, Chapter 11. Routledge.
Seifert, L., **Orth, D**., Button, C., & Davids, K. (2016). How expert climbers use perception and action during successful performance. In L. Seifert, P. Wolf, & A. Schweizer (Eds.), *Science of climbing & mountaineering*, Chapter 10. Routledge.
Button, C., **Orth, D**., Davids, K., & Seifert, L. (2016). Visual motor skill in climbing. In L. Seifert, P. Wolf, & A. Schweizer (Eds.), *Science of climbing & mountaineering*, Chapter 11. Routledge.
Davids, K., Araújo, D., Seifert, L., & **Orth, D.** (2015). Expert performance in sport: An ecological dynamics perspective In J. Baker & D. Farrow (Eds.), *Routledge Handbook of Sport Expertise* (pp. 130-144). Routledge.
Davids, K., Brymer, E., Seifert, L., & **Orth, D.** (2014). A constraints-based approach to the acquisition of expertise in outdoor adventure sports. In K. Davids, R. Hristovski, D. Araújo, N. B. Serre, C. Button & P. Passos (Eds.), *Complex Systems in Sport* (pp. 277-292). Routledge.
Seifert, L., **Orth, D.**, Hérault, R., & Davids, K. (2013). Affordances and grasping action variability during rock climbing. In T. Davis, P. Passos, M. Dicks & Weast-Knapp, J. (Eds.), *Studies in Perception & Action XII*, (pp. 114-118).

Appendix C. French Version Introduction

C.1 Contexte

C.1.1 Variabilité motrice et compétences motrices

Il existe un consensus scientifique émergent indiquant que la variabilité du mouvement est fonctionnelle et nécessaire pour une performance de qualité (Bernstein, 1967; Davids, Glazier, Araújo, & Bartlett, 2003; Riley & Turvey, 2002), l'apprentissage (Chow, Davids, Hristovski, Araújo, & Passos, 2011) et le transfert (Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009). La variabilité motrice réfère simplement à la variance statistique observée lorsque l'on compare le comportement inter ou intra individuelle autour d'une moyenne (Riley & Turvey, 2002). Cette variabilité motrice est considérée comme fonctionnelle car elle permet l'adaptation à l'environnement, réduit le risque de blessures et facilite les changements de la coordination motrice (Davids et al., 2003).

Bernstein (1967) indique qu'une source importante de la variabilité d'un système réside dans la façon dont la redondance est gérée pour amener les différentes parties du système à avoir une relation correcte pour organiser le mouvement (Sporns & Edelman, 1993). Bernstein définit la redondance comme le fait que « plus d'un signal relatif à la motricité peut conduire à la même trajectoire d'un système donné; en outre des signaux identiques peuvent conduire à des mouvements différents dans des conditions initiales identiques ou non, en présence de variations dans le champ de forces externes » (Sporns & Edelman, 1993, p. 961). Plus récemment, ces deux idées ont été définies respectivement comme la dégénérescence (structures non-identiques recrutées pour une tâche similaire) et pluripotentialité (une structure recrutée pour une sélection de tâches non identiques) ; tandis que la redondance réfère à des structures identiques, recrutées pour la même tâche (Mason, 2010, 2014; Mason, Winter, & Grignolio, 2015).

La variabilité du mouvement, par conséquent, renvoie à la façon dont la dégénérescence et la redondance neurobiologique sont coordonnées (Tononi, Sporns, & Edelman, 1999). Selon Edelman et Gally (2001), la dégénérescence et la redondance sont exploitées pour dissiper les sources d'énergie externes du système qui pourraient le perturber. Ce processus est expliqué par des principes d'auto-organisation (Schöner & Kelso, 1988; Sumpter, 2006) ; et l'impact sur le système est la formation de synergies fonctionnelles temporaires en regroupant les muscles et les articulations pour agir d'une manière unifiée (Kelso, 2012; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984). À ces égards, le système peut être coordonné, sans contrôle direct de chaque degré de liberté (Turvey, 1990). Cette flexibilité inhérente, soutient la transition entre les états stables et potentiellement l'émergence de nouveaux états du système si nécessaire (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003).

Kelso (2012) décrit les différents régimes de coordination qui peuvent être identifiés ; ceux ci incluent la mono-stabilité (où un seul pattern de coordination motrice est stable), la multi-stabilité (lorsque deux ou plusieurs patterns de coordination motrice sont stables) et le régime de méta-stable (qui correspond à des zones de transition se caractérisant par des tendances à la stabilité et instabilité de patterns de coordination). Un comportement méta-stable peut émerger lorsque des contraintes viennent contester la stabilité de l'état stable existant au point qu'il brise toutes les symétries existantes (Kelso, 2008) et place la personne sur le(s) bord(s) d'états stables plus viable (Warren, 2006). L'importance de la méta-stabilité dans l'apprentissage moteur réside dans un mécanisme qui sous-tend l'émergence de nouveaux états de coordination (Kelso, 2012).

Les contraintes jouent donc un rôle important dans la réduction de la dimension de l'espace de travail perceptivo-moteur (Newell, 1996; Newell, Liu, & Mayer-Kress, 2003; Sporns & Edelman, 1993). Ces contraintes réfèrent aux facteurs qui délimitent la coordination des mouvements et correspondent aux propriétés des individus, de l'environnement et de la tâche (Davids et al., 2003; Newell, 1986). Les affordances sont une source supplémentaire de contrainte sur la coordination des mouvements (Riccio & Stoffregen, 1988). Les affordances font références aux possibilités de comportements qui sont perçues sur la base des relations informationnelles entre l'individu et l'environnement (Gibson, 1979). La réalisation des affordances se reflète dans des actions telles que les états qualitatifs de coordination (par exemple ramper, marcher, grimper (Warren, 2006)). Enfin, par des modification des contraintes, une (ré) organisation du système de mouvement (telle que la transition d'une marche à une allure de course (Farley & Taylor, 1991)) peut refléter une adaptation à des variables informationnelles clés.

C.1.2 Exploiter la variabilité d'améliorer des compétences

La variabilité du mouvement est à la fois fonctionnelle et nécessaire, car elle permet des adaptations de l'individu par rapport à son environnement pendant l'exécution et à travers l'apprentissage (Chow et al., 2011). Une implication importante de la variabilité du mouvement induite lors de la pratique est qu'une exploration fonctionnelle plus étendue de la dégénérescence pourrait conduire à plus grande résilience et la transférabilité des compétences (Chow et al., 2011; Friston & Price, 2003; Mason et al., 2015; Noppeney, Friston, & Price, 2004). Les praticiens peuvent influencer les principes d'organisation du système (i) en changeant les paramètres spécifiques qui entravent la coordination, (ii) en guidant les apprenants à explorer différents états d'organisation en relations avec les informations nécessaires pour la réalisation des objectifs (Chow et al., 2011), (iii) en encourageant des adaptations en étroite relation avec les contraintes présentes lors de la pratique (Kelso, 2008). En effet, induire de la variabilité lors de la pratique a montré une bonne corrélation avec une meilleure rétention et transfert de compétences (Chow, 2013; Magill & Hall, 1990; Ranganathan & Newell, 2013; Schöllhorn et al., 2009).

Le transfert des compétences et de l'apprentissage se produit lorsque la formation dans un contexte affecte la performance et l'apprentissage dans un contexte différent (Adams, 1987; Carroll, Riek, & Carson, 2001; Newell, 1996). Par conséquent, le transfert est utile pour faciliter l'activité physique effectuée pendant l'apprentissage et un autre contexte comme une situation de compétition (Lopes, Rodrigues, Maia, & Malina, 2011; Rinne, Pasanen, Miilunpalo, & Mälkiä, 2010; Vandorpe et al., 2012). Un intervention qui induit de la variabilité comme (i) l'ordre dans lequel des actions sont pratiquées (Porter & Magill, 2010) ou ii) l'augmentation du nombre de conditions de pratique (Huet et al., 2011) ont conduit à de bien meilleurs effets de transfert. Le mécanisme qui sous-tend le transfert concerne l'exploration de l'espace de travail perceptivo-moteur, qui est d'autant plus induite par l'intervention d'une grande variabilité de mouvement ; cela offre la possibilité à l'individu de localiser des patterns de coordination plus efficaces et les relations information-mouvement qui soutiennent la performance (Chow et al., 2011; Huet et al., 2011; Lin, Fisher, Winstein, Wu, & Gordon, 2008; Schöllhorn et al., 2009; Stoffregen, Bardy, Smart, & Pagulayan, 2003).

Un autre point de vue est que la nécessité d'adapter le comportement aux contextes de performance qui induisent la variabilité est une propriété qui est partagée avec les contextes de transfert (Araújo, Davids, & Hristovski, 2006). Par conséquent, pour les personnes visant à transférer leur expérience à un autre contexte, un avantage peut être de développer des applications pratiques qui simulent des niveaux de variabilité correspondants à ceux des contraintes de la pratique (Araújo, Davids, & Passos, 2007; Travassos, Duarte, Vilar, Davids, & Araújo, 2012)). En effet, la possibilité de transférer l'apprentissage est idéalement corrélée avec les propriétés de l'expertise. Une des principales conclusions des analyses des experts est leur capacité supérieure à transférer leurs compétences par rapport à des individus moins qualifiés (Rosalie & Müller, 2012; Seifert, Button, & Davids, 2013). Une raison à cela, selon Seifert et al. (2013), est que les milieux de pratique experts sont largement impactés par la variabilité de l'environnement, nécessitant régulièrement des comportements adaptatifs (voir également, (Baker, Cote, & Abernethy, 2003; Phillips, Davids, Renshaw, & Portus, 2010)).

Dans un but d'induire une variabilité fonctionnelle durant l'apprentissage, une approche fondée sur la théorie des systèmes complexes est de concevoir des tâches qui amènent les individus dans des régimes de fonctionnement méta-stable (Hristovski, Davids, & Araújo, 2006, 2009; Pinder, Davids, & Renshaw, 2012; Seifert et al., 2014; Seifert, Orth, Hérault, & Davids, 2013). Les individus peuvent être amenés à travailler sous un régime méta-stable lorsque les contraintes sont manipulées de manière à créer un chevauchement dans le paysage des affordances (Hristovski, Davids, Araújo, & Button, 2006; Pinder et al., 2012). Par exemple, Hristovski et al. (2006) ont mis en évidence que le fait de faire varier de la distance entre les boxeurs et un sac à frapper lors de la pratique facilite la détection des affordances et permet de faire émerger un riche éventail de techniques de frappe. Ces résultats ont montré que pratiquer dans un régime méta-stable permet d'explorer spontanément différents patterns de coordination de mouvements (Hristovski, Davids, Araújo, et al., 2006). Bien que le mécanisme destiné à induire une méta-stabilité semble être conceptuellement connu, l'utilité de ce régime au cours de la pratique n'a pas été testée. Une hypothèse est que la méta-stabilité permet une plus large exploration de la dégénérescence et de la pluri-potentialité d'un système lorsqu'il est orienté vers un but (Chow et al., 2011). Autrement dit, des conditions qui favorisent la variabilité du mouvement lors de la pratique devraient conduire à l'acquisition de nouvelles compétences et l'amélioration du transfert de compétence (Chow et al., 2011).

C.2 Problématique

La thèse vise à déterminer comment les relations environnement-performance permettent de faciliter l'apprentissage et le transfert de compétences d'une habileté multi-articulaire, puis de déterminer quels mécanismes aident à améliorer le transfert de l'apprentissage en fonction de la pratique.

Les questions de recherche abordées dans cette thèse sont:

(1) Que nous apprennent les cadres et les modèles théoriques sur l'acquisition de nouvelles compétences dans des contextes complexes, écologiques et émergents d'activité physique ? Quelles sont les priorités de recherche dans ce domaine ?

(2) Quels types d'activités physiques peuvent être appropriées pour enquêter sur l'acquisition et le transfert de compétences multi-articulaires

(3) Les données recueillies soutiennent-elles les problématiques annoncées selon le cadre théorique adopté ? ?

(4) Quelles stratégies peuvent être développées pour améliorer l'acquisition de compétences dans les milieux de l'activité physique ?

C.3 Base conceptuelle de la Thèse

La variabilité du mouvement est fonctionnelle et nécessaire pour (i) réaliser une performance experte (Bernstein, 1967), (ii) apprendre une tâche (Chow et al., 2011) et (iii) transférer les compétences acquises dans diverses situations (Seifert, Button, et al., 2013). Malgré ces présupposés généraux, il apparaît un manque de travaux évaluant le rôle de la variabilité du mouvement afin de faciliter le transfert de compétences dans divers environnements complexes (Araújo et al., 2007; Rosalie & Müller, 2012; Seifert, Wattebled, et al., 2013). Cette thèse évalue donc les mécanismes théoriques clés pour l'acquisition de compétences, en utilisant l'escalade comme objet d'étude.

Bien que la conception efficace des contraintes de pratique est largement considérée comme une partie essentielle de l'amélioration de l'acquisition de compétences (Moy, Renshaw, & Davids, 2014), un certain nombre d'études a mis en évidence d'importants points supplémentaires à considérer.

Principalement, les études démontrent que l'acquisition de compétences peut être améliorée et renforcée par la répétition d'un modèle de mouvement idéalisé (Brisson & Alain, 1996; Chow, 2013; Moy et al., 2014; Schöllhorn et al., 2009; Seifert, Button, et al., 2013). À ce jour, peu d'études peuvent être considérée comme ayant évalué le rôle de la variabilité lors de tâches pratiques qui simulent les contraintes sur l'acquisition de compétences. Par conséquent, il est important d'aborder ce manque théorique concernant la variabilité du mouvement (et les contraintes associées à celui-ci) dans l'acquisition et le transfert de compétences.

Il peut être difficile de saisir le rôle *fonctionnel* de la variabilité du mouvement puisque les théories traditionnelles ont souligné l'intérêt de la répétition d'un mouvement idéal dans la performance (Ericsson, Krampe, & Tesch-Römer, 1993) (par exemple, une phase relative particulière entre deux segments (e.g., Schöner, Zanone, & Kelso, 1992)). En revanche, de nombreuses études ont montré des associations entre la complexité des contraintes en fonction desquelles se produit le mouvement et la variabilité de celui-ci (Dicks, Button, & Davids, 2010; Mann, Williams, Ward, & Janelle, 2007; Orth, Davids, Araújo, Renshaw, & Passos, 2014; Pinder, Davids, Renshaw, & Araújo, 2011; Travassos et al., 2013; Travassos et al., 2012). Cependant, plus de recherches sont nécessaires pour comprendre le rôle de la complexité de ces contraintes lors de l'acquisition de compétences (Newell, 1986; Wulf & Shea, 2002). Actuellement, l'évaluation de la variabilité lors de l'apprentissage de compétences multi-articulaires a été réalisée aussi bien lors d'activités cycliques continues (Hong & Newell, 2006; Nourrit-Lucas, Tossa, Zélic, & Delignières, 2014; Nourrit et al., 2003; Teulier & Delignières, 2007; Teulier, Nourrit, & Delignières, 2006) que d'actions dites discrètes (Barris, Farrow, & Davids, 2014; Chow, Davids, Button, & Koh, 2008; Chow, Davids, Button, & Rein, 2008). Cependant, aborder l'acquisition des coordinations multi-articulaires est un défi majeur qui doit être adressé pour comprendre le transfert de l'apprentissage au travers de nombreuses activités physiques. Actuellement, il n'existe pas de mouvements « modèles » pour évaluer l'apprentissage dans ces tâches, ce qui contraint à développer une base théorique de recherche viable pour de futurs programmes de travail.

Des études antérieures se sont focalisées sur le rôle des contraintes qui induisent de la variabilité dans un mouvement adaptatif réalisé par une population experte (Hristovski, Davids, Araújo, et al., 2006; Pinder et al., 2012). Mais la variabilité du mouvement, tel que le *comportement exploratoire*, peut ne pas être considérée comme fonctionnelle pour les experts alors que cela peut être le cas pour les apprenants inexpérimentés qui ont encore besoin d'explorer de nouveaux modes de coordination. De plus, si des notions d'apprentissage peuvent encore être démontrées chez des individus experts, cela démontre l'importance de concevoir des situations de pratiques avec des contraintes pour les apprenants. Même chez les individus inexpérimentés face à une nouvelle tâche d'apprentissage, l'exploration peut devenir rapidement limitée (Chow, Davids, Button, & Koh, 2007; Cordier, Mendès-France, Pailhous, & Bolon, 1994). Si l'apprentissage dans un environnement contraignant induit un régime de mouvements méta-stables, cela confirmerait que les stratégies pédagogiques sont adaptées à l'émergence de contraintes pour réaliser des performances améliorées.

Améliorer leurs compétences est une motivation centrale pour lesquelles les individus participent à une activité physique, avec pour objectif de transférer ces apprentissages dans d’autres contextes (Carroll et al., 2001). Et pourtant, ces comportements communs aux yeux de tous sont mal compris dans la littérature (Chow, 2013). La conception efficace de situations d'apprentissage doit être mise en relation avec des données qui peuvent caractériser ce comportement dans un environnement de contraintes : cela permettra de fournir une preuve claire que, après l'entraînement, les apprenants peuvent réaliser un mouvement de la même manière que des personnes qui ont «naturellement» acquis leur compétence. Le cadre conceptuel global de cette thèse est résumé dans la figure 1.1.

Variabilité de mouvement

↓

Variabilité motrice et compétences motrices

↓

Exploiter la variabilité afin d'améliorer des compétences

↓

Explorer les priorités de recherche **Chapitre 2**: L'acquisition de la variabilité fonctionnelle : une revue de la littérature ***Cadre théorique pour la compréhension du « transfert de compétences »***
Développer un objet de recherche **Chapitre 3**: Coordination en l'escalade : revue de littérature ***Une activité physique exigeant le transfert de compétences***
Développer des méthodes **Chapitre 4**: Efficience chez les grimpeurs experts : revue de littérature ***Développer des techniques de mesure de la coordination experte***
Confirmer le modèle théorique **Chapitre 5**: Les contraintes favorisant un régime de mouvement méta-stable dans une tâche complexe multi- articulaire • Effet de la pratique • Effet du niveau de compétence
Evaluer les mécanismes **Chapitre 6** Savoir-faire et transfert de compétences dans le cadre de l'activité physique • Effet de compétences existantes • Acquisition de nouvelles compétences
Identifier les stratégies de mise en œuvre **Chapitre 7**: Stratégies d'acquisition de compétences en escalade • Élaborer des stratégies pour la mise en œuvre des résultats dans des contextes appliqués

Figure C-8-1. Base conceptuelle de la Thèse.

C.4 Aperçu de la thèse

Cette thèse est présentée sous la forme d'articles scientifiques. En tant que tel, chaque chapitre peut être abordé séparément. Dans le chapitre 2, par le biais d'une revue de littérature, une perspective est établie sur la façon dont la compétence peut être conceptualisée comme une *propriété émergente de l'apprentissage,* impliquant une exploration motrice. Deux termes théoriques en relation avec la conception des tâches d'apprentissages et l'apparition de la variabilité fonctionnelle du mouvement doivent être explicités. Premièrement, il a été constaté que plus les conditions de test sont représentatives du contexte de compétition, plus la variabilité de mouvement est utile pour la performance. Deuxièmement, lorsqu'une condition de pratique peut induire différentes réponses motrices, les individus ont tendance à explorer de façon plus spontanée un grand nombre de comportements. De façon similaire, dans un nouveau contexte de performance, les individus ont également tendance à explorer de nouveaux comportements afin de répondre au contexte de pratique. Cependant, l'écart entre la variabilité de mouvement observée durant la pratique et le transfert de compétence n'a pas encore été étudié dans la littérature.

Dans les chapitres 3 et 4 l'activité de l'escalade est utilisée comme outil d'étude de la thèse car elle comporte aussi bien des actions discrètes que cycliques. Dans le chapitre 3, un examen systématique de la littérature est réalisé afin d'examiner en détail l'impact des contraintes au cours de la performance, avec une vision toute particulière appliquée à l'activité escalade. Dans le chapitre 4, les points forts et les limites des méthodes existantes pour mesurer l'expertise en l'escalade sont passés en revue. En conclusion, deux indicateurs spatio-temporels de la fluidité sont présentés en fonction des intentions du grimpeur et ceci pour capturer le comportement exploratoire et expert.

Dans le chapitre 5, les effets de la pratique dans un environnement de contraintes sont testés, pouvant alors induire de la méta-stabilité dans le comportement. Il a été trouvé que la méta-stabilité supporte l'acquisition de compétences en escalade et le transfert de celles-ci dans d'autres contextes de pratique.

Dans le chapitre 6, l'expérience se divise en trois parties. Dans la première, les effets des compétences existantes de chaque individu sur la performance en escalade ont été testés. Dans la seconde expérimentation, les effets de l'expérience sur la stabilité des patterns de mouvements existant ont été testés. Les résultats combinés des deux premières expérimentations montrent que les grimpeurs experts ont réduit leurs répertoires de mouvements. Dans la troisième expérimentation, un groupe d'apprenants en escalade a réalisé un protocole de sept semaines sur une voie de niveau standard. Il a été démontré que les débutants ont pu acquérir un nouveau répertoire de mouvements, concomitants avec ceux observés chez les grimpeurs plus confirmés.

Dans le chapitre 7, les résultats clés de la présente thèse sont synthétisés et résumés. Je souligne le fait qu'un comportement exploratoire est un mécanisme clé dans l'acquisition de nouvelles compétences et dans le transfert de celles-ci. Je discute également l'impact du cadre théorique pour créer de nouveaux contextes de pratique dans le domaine de l'activité physique.

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Appendix D. French Version Conclusions

Une raison importante de la popularité de l’activité physique réside dans le fait d’apprendre et d’améliorer des compétences motrices. Un cadre théorique de recherche est nécessaire pour observer et analyser ces modalités d’apprentissage dans un contexte écologique de pratique. La thèse investigue les théories d’acquisition de compétence appliquées à la pratique de l’escalade.

Plus précisément, ce travail vise à déterminer comment les relations environnement-performance soutiennent l'acquisition de compétences multi-articulaires (capacité d'améliorer les performances dans un contexte écologique de pratique) et ensuite, de présenter les mécanismes qui améliorent le transfert de ces compétences (amélioration de la performance ou de l'apprentissage dans des conditions différentes de pratique). Les problématiques de travail adressées par cette thèse étaient : (1) Quels sont les cadres théorique expliquant l'acquisition de compétences dans des contextes complexes d'activités physiques ? Et quelles sont les priorités de recherche dans ce domaine ? (2) Quelles sont les objets de recherche et de mesures viables pour enquêter sur l'acquisition de compétences multi-articulaires complexes ? (3) Les données acquises dans des contextes d'activités physiques supportent-elles le cadre théorique adopté ? (4) Comment ces mécanismes peuvent être utilisés pour expliquer l'apprentissage de nouvelles compétences évaluées ? (5) Quelles stratégies peuvent être développées pour améliorer l'acquisition de compétences dans le milieu des activités physiques ?

Grâce à une revue de la littérature, une perspective est établie sur la façon dont le comportement peut être conceptualisé comme un phénomène émergent. Cela implique l'exploration des degrés de liberté du système. Deux concepts théoriques ont émergé en ce qui concerne la conception des tâches et les recherches sur l'apprentissage. Tout d'abord, le concept de représentativité de la tâche : il a été constaté que plus la tâche représente le contexte réel de performance, plus la variabilité de mouvement du système est considérée comme un déterminant de cette performance.

Deuxièmement, le concept de méta-stabilité reflète la possibilité pour les individus d'explorer spontanément une plus grande variété de comportements qualitativement différents lorsque le contexte de pratique en offre la possibilité. Dans chaque cas, la représentativité de la tâche et le phénomène de méta-stabilité semblent faciliter l'apparition de comportements exploratoires spontanés, considérés comme une indication clé de l'apprentissage de l'individu. Des recherches supplémentaires sont cependant nécessaires pour renforcer le cadre théorique actuel, notamment en tenant compte des liens entre la représentativité de la tâche, le phénomène de méta-stabilité et la variabilité fonctionnelle de mouvement. Ces phénomènes doivent être mis en regard du comportement de l'individu lors de l'apprentissage mais également dans des conditions de transfert de compétences. Il est donc suggéré qu'une importante priorité de recherche doit être donnée aux processus d'apprentissages moteurs et de transfert de compétences dans des contextes correspondant à ceux dans lesquels les individus sont activement impliqués.

La plupart des études précédentes sur l'apprentissage moteur impliquant des tâches multi-articulaires complexes ont été conçues pour tester la coordination des mouvements dans des tâches d'interception discrètes ou dans des tâches continues cycliques. Toutefois, la majorité des activités physiques se induisent les deux catégories de séquences motrices (cycliques et discrètes). Ainsi, l'intérêt de cette étude était de se focaliser sur une activité physique répondant à ce critère, où les individus utilisent à la fois une locomotion cyclique et des comportements moteurs discrets. L'activité « escalade » est donc proposée afin de fournir un nouvel objet d'étude pour répondre aux priorités des recherches actuelles. Une revue de littérature a été réalisée permettant d'examiner en détail l'impact des compétences, de la pratique et de la manipulation de contraintes (facteurs environnementaux, de tâche et organismiques) sur la coordination motrice lors des activités d'escalade. De plus amples recherches sont cependant nécessaires pour (i) comprendre l'impact des différentes conditions d'intervention sur l'apprentissage et (ii) évaluer des individus avec différents niveaux d'expérience afin de déterminer quelles sont les compétences spécifiques qu'exige escalade.

Les études antérieures se focalisant sur la présence de méta-stabilité dans les tâches multi-articulaires complexes réalisées par des experts n'ont pas montré un effet de la pratique répétée. Si l'apprentissage est étudié chez des experts sous l'effet de contraintes qui induisent la présence de méta-stabilité, l'observation du comportement au cours d'essais répétés est nécessaire pour confirmer cette hypothèse. En outre, si les effets d'apprentissage doivent être attribués à la conception d'une « pratique méta-stable », plusieurs conditions doivent être évaluées par rapport à un test de transfert de compétences. Il est également difficile de savoir comment les individus inexpérimentés réagissent lorsqu'ils sont situés dans une région de méta-stabilité lors de leur pratique. Pour établir les orientations futures de la recherche, il a été observé (i) la pratique d'un groupe de grimpeurs experts et d'un groupe de grimpeurs inexpérimentés dans des conditions de tâches méta-stables et (ii) les capacités de transfert de leurs habiletés après la pratique. Une analyse de leur comportement exploratoire au niveau de la hanche et de la main a été effectuée en utilisant une procédure de suivi semi-automatique combiné avec des annotations manuelles. Cette étude a montré que l'apprentissage moteur est apparu à différents niveaux, aussi bien au niveau des mains que du reste du corps. La quantité d'apprentissage et la vitesse à laquelle celui-ci a eu lieu ont été mises en lien avec le niveau des participants. Les grimpeurs avec plus d'expérience sont, de par leur grand temps de pratique, formatés à apprendre dans des conditions de méta-stabilité. Les grimpeurs moins expérimentés ont été conduits à apprendre sur une voie d'escalade qui a nécessité l'utilisation de patterns moteurs avancés, spécifiques à l'activité, en plus de l'apprentissage en conditions de méta-stabilité. Pour le transfert de compétences, et contrairement à nos attentes, ce sont les individus expérimentés qui ont montré le plus d'exploration qui ont développé les meilleures performances.

Les individus présentent généralement des modèles stables de coordination qui peuvent provoquer une résistance ou une inhibition au développement de comportements fonctionnels répondant à un nouvel environnement de contraintes. Certaines procédures d'analyses déterminent la stabilité de la coordination des mouvements existants en exigeant de l'individu qu'il utilise une importante gamme de modèles de coordination. Pour comprendre l'effet des compétences existantes sur le comportement dans des conditions qui induisent de la méta-stabilité, une série d'expériences qui forçait les débutants et les grimpeurs expérimentés à adopter différents patterns de coordinations en escalade a été mise en place. Dans ces expériences, un suivi automatique de la position de la hanche en utilisant un filtre de Kalman basique a été utilisé. Les données temporelles d'un capteur positionné au niveau de la hanche ont permis l'évaluation du comportement (rotation du tronc et immobilité/mouvement) entre le corps du grimpeur et le mur d'escalade. Enfin, l'orientation de la saisie des prises au mur a été évaluée en utilisant la vidéo. Les résultats ont montré (i) des effets significatifs de l'expérience antérieure et (ii) une grande stabilité des patterns de coordination utilisés par les grimpeurs. Les sujets sans expérience en escalade ont tendance à saisir les prises en utilisant des techniques simples tandis que les grimpeurs expérimentés utilisent un plus large répertoire d'actions de préhension. Il a également été constaté que les sujets inexpérimentés ont pu grimper en utilisant ce qui a été considéré comme un *modèle de coordination corps-mur avancé*, qui fut cependant moins fluide que celui réalisé par les grimpeurs expérimentés. Fait intéressant, les sujets qui sont tombés au cours de la procédure de test étaient incapables d'utiliser ce *modèle de coordination corps-mur avancé* lors du déplacement. Une étude d'intervention impliquant la pratique de l'escalade dans des conditions qui soutiennent le phénomène de méta-stabilité a ensuite été entreprise pour ces individus. Il a été confirmé que l'exposition prolongée à une tâche dite « méta-stablé» peut conduire à l'acquisition de comportements représentatifs des compétences acquises par des sujets expérimentés en escalade indoor. Un test avant / après a été utilisé afin de souligner l'émergence de *modèles de coordination corps-mur* avancés. Un test de transfert de compétences a également révélé des niveaux de performance comparables à ceux d'un groupe de grimpeurs plus expérimentés.

Les résultats de cette recherche suggèrent que dans les motricités complexes multi-articulaires, *l'exploration* est un mécanisme clé (i) pour acquérir de nouvelles compétences et (ii) pour maintenir ces compétences dans des conditions de transfert d'habiletés motrices. Ces données démontrent que la présence de *méta-stabilité* supporte la capacité d'adaptation des performances à la variabilité inhérente aux activités physiques telle que l'escalade. Ces idées ont été discutées en montrant que la façon de concevoir la voie (l'orientation des prises et la capacité de maintien de l'individu sur celles-ci) peut être utilisée pour établir des tâches pratiques représentatives de l'activité, dans le but d'acquérir de nouvelles compétences.

Pour résumer, cette étude s'ajoute à un corps de la littérature certes limité, mais de plus en plus consistant. En effet, elle a permis d'évaluer l'impact de l'entraînement sur le transfert des compétences et d'améliorer nos connaissances sur les contraintes qui influencent la relation individu-environnement lors de la pratique. Bien que la recherche soit limitée à un échantillon de sujets en Haute-Normandie (France), les méthodes développées dans cette thèse seront utiles à d'autres chercheurs qui étudient les relations individu-environnement dans des tâches multi-articulaires complexes. Ces résultats peuvent également avoir un intérêt plus appliqué, notamment en ce qui concerne la création de contextes d'apprentissages spécifiques favorisant l'acquisition de compétences transférables.

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DYNAMICS OF ACQUIRING ADAPTIVE SKILLS IN A COMPLEX MULTI-ARTICULAR TASK:

CONSTRAINTS ON META-STABLE ACTIONS

Notre travail, prenant pour cadre la théorie écologique appliquée aux systèmes dynamiques, plaide en faveur d'une redéfinition du concept d'apprentissage des coordinations motrices. En prenant comme support la pratique de l'escalade, nous avons tenté de déterminer la place prise par l'interaction environnement-performance sur l'acquisition de compétences motrices en identifiant les mécanismes à l'origine de l'apprentissage. Pour cela, nous avons mis en place différents contextes d'apprentissage qui induisent un régime de métastabilité, mécanisme à travers lequel l'individu exploite des compétences acquises pour en développer de nouvelles. Des mesures ont donc été faites pour déterminer les effets de l'entraînement en escalade sur la stabilité des patterns de coordination. Après entraînement, notre analyse montre qu'un groupe de débutant adopte des coordinations motrices semblables à un groupe plus expérimenté en escalade. Des mouvements plus fluides dans des voies inconnues ont en effet été observés, un phénomène étroitement lié à une hausse du comportement exploratoire au cours des séances d'entraînement. Au cours de ces premières séances, le comportement exploratoire était corrélé avec une mauvaise performance. Après l'entraînement, une augmentation des comportements exploratoires est constatée lorsque le débutant est invité à découvrir une nouvelle voie, ce phénomène étant cette fois ci étroitement lié à une hausse de la performance. Nous mettons ainsi en avant que l'exploration joue un rôle clé sur le développement de nouvelles compétences motrices, ce qui accrédite le concept de transfert de compétences. Ce travail de thèse va donc dans le sens des concepts théoriques clés de la théorie écologique tels que l'affordance, la dégénérescence, la métastabilité pour mettre en place des situations d'apprentissages.

Mots clés: apprentissage, dégenérescence, escalade, exploration, métastabilité

This thesis, based on key ideas in ecological dynamics, presents data supporting a re-definition of the concept of learning and transfer of skills, using climbing as the research vehicle. The research programme sought to determine how environment-performance relationships support the acquisition of multi-articular skills, attempting to identify mechanisms that support improved transfer of learning due to practice. Specifically, these were learning contexts that induced behavioural meta-stability (a coexistence of stable and unstable coordination tendencies, and consequently promoted exploration of different motor behaviours), a mechanism through which individuals may exploit existing skills to also explore new, potentially more effective coordination modes. The programme of work addressed by this thesis was: (1) how skill was related to the exploration of behavioural opportunities (affordances) during performance; (2) how movement variability was related to performance during practice, and; (3) the underpinning role of exploration in supporting the transfer of learning. A pre- and post-test intervention design used a scanning procedure to determine the effect of practice on the stability of different climbing patterns of coordination. A group of beginners were shown to transition toward advanced styles of climbing and their performance on a transfer test revealed comparable levels of movement pattern stability to that of a more experienced group. Better climbing fluency in unfamiliar routes was related to increased exploratory behaviour during training conditions. In early practice, exploratory behaviour was associated with poor performance. After practice, increased exploration under transfer conditions was associated with better performance. The research evidence in this thesis suggests that, in complex multi-articular skills, exploration is a key mechanism for acquiring new skills and can support skills transfer.

Key words: affordances, climbing, metastability, skill acquisition, transfer