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Analysis of perceptual-motor calibration processes in indoor climbing

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Analysis of perceptual-motor calibration processes in indoor climbing

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USE OF THESIS

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Chapter 1: Introduction

1.1. Background

In most daily interception tasks, people can usually move freely towards objects to make them easier to reach. In rock climbing, however, the position of the feet and hands are constrained by available holds or features of the climbing surface. When reaching to grasp another hold, climbers must control the torques created by the gravitational force acting on their body and the reaction forces acting at their points of contact. The torque experienced by the climber is increased when reaching horizontally, as the gravitational force is farther from the axis of rotation (foot on the foot hold) than when reaching vertically. Climbers often compensate for anticipated torques by making small postural adjustments prior to reaching and grasping (Bouisset & Zattara, 1981, 1987; Commissaris, Toussaint, & Hirschfeld, 2001; Stapley, Pozzo, & Grishin, 1998).

To help anticipate postures that are required to use available holds, skilled climbers will mentally rehearse the route beforehand, simulating the required hand positions. Using route previews has been shown to improve climbing performance (Pezzulo, Barca, Bocconi, & Borghi, 2010). For route previews to be useful, the climber must accurately perceive how far they can reach from anticipated positions during the climb and whether they can grasp the hold. However, perceiving the extent of the reach is not sufficient because the climber needs to be able to also grasp and utilise the handhold. These affordances (reach-ness, grasp-ness, and use-ness) are interrelated and nested (Bruineberg & Rietveld, 2014; Rietveld & Kiverstein, 2014). In order for a climber to climb a route (the task), they need to determine whether the holds are within their arm span (reach-ness), and whether they are able to use the holds to support their weight (grasp-ness). Moreover, the climber must be able to use the holds to coordinate movement and regulate their posture (use-ness). For this thesis, reaching affordances will be referred to collectively, however, we acknowledge that there are multiple embedded components.

Task experience has shown to improve perceptual accuracy (Boschker & Barker, 2002; Hove, Riley, & Shockley, 2006), but it is not clear to what extent experience transfers from task to task (i.e. does experience in daily reaching activities transfer to perceiving maximal reach- and grasp-ness in climbing?). Moreover, as climbers' reach actions change (reach to grasp and grasp to use), so do the constraints. For example, reach-ness relates to the perceiver's body dimensions, grasp-ness further relates to the strength necessary to complete the task and use-ness relates to coordination and postural regulation. The primary aim of this thesis is to identify factors that affect how people perceive and transition between the limits of their ability to reach, grasp and use climbing handholds. A second aim is to determine how accurately determining maximal boundary of reach- and grasp-ness translates into climbing fluency.

When reaching for an object, obvious functional features like handles influence how humans interact with the object (Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009; Symes, Ellis, & Tucker, 2007). Presenting participants with a familiar object evokes motor actions associated with the object (Tucker & Ellis, 1998; Young Yoon & Humphreys, 2007). For example, when reaching for a hammer, we tend to reach for the handle and not the head. While the use of familiar objects has been crucial in understanding how people perceive reaching affordances (Linkenauger et al., 2009; Tucker & Ellis, 1998), greater understanding is needed on how people perceive maximal reach- and grasp-ness for objects like climbing holds that can have ambiguous geometric features.

Figure 1. Example of large climbs hold with ambiguous (left) and distinct features (right)

Arguably, indoor climbing holds present climbers with ambiguous features about how they might be used (Button, Orth, Davids, & Seifert, 2018). Indeed, the geometric properties of a hold like shape ambiguity (see Figure 1), orientation (Fuss & Niegl, 2012; Quaine, Vigouroux, & Martin, 2003) and size (Bourdin, Teasdale, & Nougier, 1998a) can affect the difficulty of a climbing route. Research shows that orientating a hammer's handle away from the participant (changing an object's orientation) affects how far people perceive it to be (Linkenauger et al., 2009) and how they grasp it (Baud-Bovy & Soechting, 2001; Sartori, Straulino, & Castiello, 2011). For example, people adopt different grasping postures – over or underhand grasp when a hammer's handle is facing away or towards their grasping hand, respectively (Linkenauger et al., 2009). Despite the changes to hold size and orientation, experienced climbers appear to accurately perceive their maximal action capabilities and adjust their body position when needed. It is currently unclear how or whether experienced climbers are able to perceive how features like object size and orientation affect their perception of reach-, grasp- and use-ness.

The reciprocal fit between a person's capabilities and features of the environment provides opportunities for action, often referred to as "affordances" (Gibson, 1979; Turvey, 1992; Wagman, 2008). Affordance perception is a dynamic process, in which accurate perception relies on the perceiver's ability to attune to the demands of the task and calibrate the capabilities effectively. To perceive accurately, a person must be able to attend to the correct information variable. Traditionally, a novice may attend to a variable that ambiguously relates to the perceived property (non-specifying information variable). The perceiver perceptual accuracy can improve when they converge on the information variable that relates one-to-one to the perceived property (specifying information variable) (Withagen & Michaels, 2005; Withagen & Van Wermeskerken, 2009). Perceiving opportunities for specific actions requires *perceptual attunement to relevant informational variables*, meaning that children need to develop a range of perceptual variables from various modalities (haptic, kinesthesis, auditory, visual) that specify a relevant property of a performance environment (Fajen et al., 2009; Jacobs & Michaels, 2007). A relevant property indicates that the property enables the children to functionally achieve specific task goals. Moreover, the perceiver must be able to scale their physical and action capabilities to the demands of the task by mapping between units the measurement is taken and some other known units - a process referred to as calibration (Fajen, 2005a, 2005b, 2005c; Fajen, Riley, & Turvey, 2009). For example, when reaching for a glass, the perceiver would need to map the distance from arm-span and meters. To be perceptually accurate, a perceiver must be able to attune to *and* calibrate the task. However, the information the perceiver relies on to be perceptually accurate can change between or within a task (e.g. carrying weight or changing from reach to grasp). Individuals must also be able to reattune and calibrate to new constraints.

If a person's capabilities change, so will their affordances. Perception of an affordance is a prospective act (Wagman, 2012; Wagman, Thomas, McBride, & Day, 2013), that changes over long (e.g. aging) and short time (e.g. injury, fatigue, etc) scales. For example, an object that was once unreachable may appear within reach if the perceiver uses a tool such as a ladder (Witt, Proffitt, & Epstein, 2005). Furthermore, affordances change over both spatial and temporal scales (Gibson, 1979), i.e. an affordance can appear or disappear from one moment to the next like when trying to run through a gap in rugby.

Both the environment and the capabilities of the perceiver can change over time. Research has shown that when participants receive feedback, they are able to rapidly calibrate when their action capabilities suddenly change (Wagman & Van Norman, 2011). For example, people perceive they can step on higher steps than usual when blocks are attached to their feet (Mark, 1987); reach further when reaching with a tool (Wagman, Taheny, & Higuchi, 2014; Witt et al., 2005); perceive hills to be steeper and more difficult to ascend when carrying a heavy backpack (Bhalla & Proffitt, 1999) or after an exhaustive run (Bhalla & Proffitt, 1999; Proffitt, Bhalla, Gossweiler, & Midgett, 1995). Moreover, individuals perceive they cannot jump as high when encumbered with weights around their ankles (Ramenzoni, Riley, Shockley, & Davis, 2008). Therefore, when a climber embarks on a long climb that can last several days, what was perceived as reachable on the first day may not appear (or be) reachable on the last day.

1.2. Factors Affecting Perceptual Accuracy

Postural control is important when determining reach boundaries and is crucial to climbing as climbers continually move in and out of balance. According to Bourdin, Teasdale, and Nougier (1998b), postural stability prior to, during and after the grasp is the primary determinant of success, meaning that climbers must account for their postural control throughout the entire climb. Moreover, climbers must account for the effect that factors like the load, load position, and fatigue have on their ability to reach for and grasp holds and to move. While reach- and grasp-ness is important for climbing, few studies have examined affordance perception and its relationship to movement. Furthermore, much of the reach-to-grasp literature has focused on handled objects, suggesting that how people calibrate their reach-to-grasp affordances for more ambiguous features is unclear. It is posited that the perception of maximum action capabilities are affected by: orientation, fatigue, object size, body positioning, encumbrance and changes to the task goals. While some of these factors affect a person’s biodynamic capabilities (e.g. strength, mobility and flexibility), it is unlear how these affect maximal horizontal reaching and grasping affordances.

When a climber reaches for a hold or moves their leg, they remove an anchorage point creating a postural disturbance (Bouisset & Zattara, 1987) making balance harder to maintain (Quaine, Martin, & Blanchi, 1997). The direction a climber reaches can affect their ability to maintain balance by shifting their centre of mass (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Robinovitch, 1998) and affect their horizontal and vertical reach estimates differently (Fischer, 2000). It is common for climbers to reach while resting an outstretched leg against the wall to remain balanced - a manoeuvre called flagging; however, it is unclear how this affects their perception of affordances.

When climbing outdoors, it is common for climbers to carry safety gear on their harness, and possibly a backpack around their shoulders. The location where the participant places the additional load, affects the location of their centre of mass (Malek & Wagman, 2008). This displacement of the participant’s centre of mass affects how they perceive affordances, as well as perception of geometric properties such as their ability to stand on an inclined surface reduced when carrying weight above their head (Regia-Corte & Wagman, 2008) or on their back (Malek & Wagman, 2008). Despite these results, the authors were unable to find any research documenting whether the location of additional weight affects a perception of reach- and grasp-ness or hold geometric properties in climbing.

For outdoor climbers, the weight added by their safety gear is a debated topic – with many websites and discussion boards dedicated to this issue. For climbers, the amount of extra weight is often dictated by the difficulty and length of the climb. Carrying extra weight affects the perception and actualisation of affordances (Bhalla & Proffitt, 1999; Ramenzoni et al., 2008; Regia-Corte & Wagman, 2008) by increasing the energetic cost of movement (Bhalla & Proffitt, 1999; Proffitt et al., 1995) and distorting perception of the environment and action capabilities. As climbers use their arms to move by reaching for, grasping, and using holds, carrying additional weight means that climbers needs to produce a greater force to support themselves and move. However, it is unclear how the addition of weight affects their ability to perceive and actualise maximal reach- and grasp-ness.

Moreover, as climbers move through a route, they must deal with the accumulating effects of fatigue – affecting their energetic cost of movement (Proffitt, 2006). Unlike most other sports, climbers often have limited opportunities to rest, therefore, they often need to continue climbing when experiencing high levels of fatigue. To date, one study (Pijpers, Oudejans, & Bakker, 2007) has examined the effect of accumulating fatigue on perceiving the affordance of maximal reachability in climbing, finding that maximal overhead reach height only decreased when the fatigue was rated as hard or higher (RPE of 18 to 20). However, Carello et al. (1989) and Robinovitch (1998) argue that reach estimates are influenced by the participant's ability to maintain their centre of mass within their base of support, so we may expect greater discrepancies in horizontal reaching when the participant is fatigued, but this is currently unknown.

When climbing, the goal of hold use changes depending on the postural challenges faced by the climber. Climbers reach and grasp to reposition their feet or body and move. Research shows that the accuracy requirements of the task goal affect hand and finger placement (Ansuini, Giosa, Turella, Altoè, & Castiello, 2008; Ansuini, Santello, Massaccesi, & Castiello, 2006; Cohen & Rosenbaum, 2004). For example, Sartori et al. (2011) found that when the task goal required greater accuracy and control, participants placed their fingers closer to the centre of the object. However, these aforementioned studies have only examined the effect of end-goal (e.g. pour water versus moving a glass) on hand placement in manipulation tasks. Therefore, it is unknown how task goal affects the perception of maximal reach- and grasp-ness for different reach and grasp end goals.

As climbs increase in difficulty, climbing holds often get smaller and features become more ambiguous. Object geometry affects how people reach (Jeannerod, 1984) and grasp objects (Baud-Bovy & Soechting, 2001; Lederman & Wing, 2003). For example, we place our fingers closer together when grasping a concave bottle than when grasping a cylindrical bottle (Sartori et al., 2011). However, object geometry does not always represent its grasp-ness with some climbing holds being smooth and have no clear graspable surface. Despite the absence of a clear graspable feature, climbers must still grasp such holds to progress up the climb. Interestingly, the absence of a clear graspable surface, results in participants focusing on grasping closer objects (Garrido-Vásquez & Schubö, 2014), even if they are irrelevant (e.g. a climbing hold that no longer facilitates progression up the route).

Changing the orientation of an object affects how a participant perceives and interacts with it (Linkenauger et al., 2009; Seifert, Boulanger, Orth, & Davids, 2015; Seifert et al., 2014). Participants perceive objects as closer and easier to grasp when the object's functional feature (e.g. handle) is facing them. Additionally, participants respond significantly faster and more accurately when the functional feature is congruent with the responding hand

(Tucker & Ellis, 1998). The authors suggest that object orientation evokes a specific motor response; however, participants only perceived grasping objects that were familiar and had obvious functional features. In climbing, Seifert et al. (2015) showed that changing the orientation of a holds grasp-able surface affected a climber's movement pattern. Moreover, climbers grasp holds that have ambiguous features and are often incongruent with their responding hand. Despite this, little is known about the effect of climbing hold orientation on the perception of reach- and grasp-ness.

It would be of interest to investigate if climbers are more accurate than non-climbers at perceiving their maximal boundary of reach- and grasp-ness. Extensive research shows that many factors can affect affordance perception, but task experience is vital for accurate perception (Hove et al., 2006). It is unclear whether the climber's success is dictated by their ability to perceive reach- and grasp-ness. A better understanding of the generalisability of reaching experience will enable more refined training programs targeting motor simulation and action for both novice and experienced climbers.

1.3. Significance of this research

A paucity of literature exists investigating the effects of biodynamic factors on how people perceive their maximal boundary of reach- and grasp-ness and its relation to movement in climbing. While it has been established that biodynamic factors affect how people calibrate reaching distance (Choi & Mark, 2004; Mark et al., 1997), it is currently unclear how the perception of maximal action capabilities are affected by orientation, fatigue, object size, body positioning, encumbrance and changes to the task goals. Moreover, rock climbing presents a novel vehicle as a climber's movement is heavily constrained by their environment and success depends upon the ability to accurately perceive action boundaries. Therefore, the purpose of this thesis is to examine how biodynamic factors affect how people calibrate their maximal horizontal boundary of reach- and grasp-ness in climbing. The results will add to current knowledge by examining the contribution of biodynamic factors on the perception of maximal horizontal reach- and grasp-ness in climbing.

1.4. Research Questions

This research programme examines how people perceive maximal reach- and grasp-ness in climbing, and as such these questions will be limited to climbing.

1. Is experienced gained from performing daily submaximal reaching sufficient for the accurate perception of maximal horizontal reaching affordances in rock climbing?
2. How is perception of maximal horizontal boundary of reach- and grasp-ness affected by:
    a. hold size
    b. body position
    c. additional load
    d. fatigue
3. How will inducing fatigue affect how a participant calibrates distance and their movement economy?

1.5. Hypotheses

1. Experienced gained from performing daily submaximal reaching will not lead to the accurate perception of maximal reach- and grasp-ness
2. The perception of maximal horizontal reach- and grasp-ness will be affected by the hold size, body position, additional load, and fatigue
3. Fatigue will decrease how climbers calibrate distance and their movement fluidity

1.6. Limitations

All climbers participating in this study are local Western Australian climbers who climbed in climbing gyms, and such data may not be representative of the climbing population as a whole.

1. While the authors tried to represent climbing conditions, either in a gym or outdoors, all testing took place in a lab and may not be completely representative of the task.

Chapter 2: Literature Review

2.1 Background

Reaching is fundamentally important to most daily actions as it allows us to interact with objects and surfaces within our environment. The apparent ease and success displayed by healthy humans in executing complex actions is fascinating. In order to reach, grasp, and use objects, we must first perceive the relationship between our capabilities and characteristics of the environment, a concept termed “affordances” (Gibson, 1979). If the desired action is not supported by our capabilities to act, or the characteristics of the environment, the affordance will not be accurately perceived (Gibson, 1979). Perceiving an affordance is a personal, continuous process (Pepping & Li, 2000a; Turvey, 1992; Wagman, 2008) shaped by our past (Pijpers, Oudejans, & Bakker, 2007) and present experiences (Higuchi et al., 2011).

According to Vicente and Rasmussen (1990) affordances are nested over three levels: the goal of the task (why), the behaviours that would achieve the goal (what) and the various means available for performing the behaviours (how). If any of these levels change, for example, if we extend our reach by using a tool, our perception of the affordance landscape will be altered (Wagman, Cialdella, & Stoffregen, 2018). Furthermore, affordances are nested over both temporal and spatial scales (Gibson, 1979; Wagman, Cialdella, & Stoffregen, 2018); an affordance that is possible at one time may not be possible later. For example, reaching something that is moving away from us, or reaching something after our action capabilities have changed, such as when fatigued. Many factors affect our ability to accurately perceive reach- and grasp-ness, including balance (Fischer, 2000), fatigue (Pijpers et al., 2007) and encumbrance (Ramenzoni, Riley, Shockley, & Davis, 2008), but it is unclear if our perception of reach- and grasp-ness is influenced by the goal of the task. Do we perceive objects differently when the object is grasped for manipulation or for locomotion?

Rock climbing is a useful task to study how people perceive their maximal reaching capabilities and geometric properties because climbers move through a constrained environment by reaching for, grasping, and supporting themselves on objects of different shapes, textures and sizes. The climber must account for distance between objects, the effect of carrying extra weight and the role of strength, joint flexibility, and body posture - factors that have all been shown to influence how people perceive reach- and grasp-ness when manipulating an object (Choi & Mark, 2004; Mark et al., 1997). Similar to walking, a climber's success is not solely constrained by their physical characteristics (e.g. arm span), but also their ability to maintain stability prior to, during, and after the grasp (Bourdin, Teasdale, & Nougier, 1998). Moreover, climbing requires not just vertical reaching, but also horizontal and diagonal reaching, which may be more affected by the participant's ability to maintain balance (Fischer, 2000). Despite the apparent importance of stability for reaching and grasping in climbing, there remains a paucity of evidence examining its effects upon a climber's maximal boundary of reach- and grasp-ness.

Although extensive research has been published on reaching, the majority of studies have dealt with manipulating static objects and not upon reaching and grasping embedded within locomotion. Furthermore, of the studies that have dealt with reaching and grasping affordances in climbing, many have used inexperienced climbers. Therefore, the purpose of this review is to identify and explore the factors that affect the perception of maximal reach- and grasp-ness for locomotion, specifically climbing. This review has three main sections: the first will discuss the perception of reach boundaries (the action); the second section will discuss environmental factors affecting reaching boundaries (the environment) and movement; and the third section will discuss organismic factors affecting reach boundaries (the animal).

2.1 Methods

2.2.1 Literature Search Procedures

The literature search was completed using Web of Science, PubMed, and Google Scholar from 5th July to 28th November 2017. Keywords relating to reach/grasp perception (i.e., reaching, grasping, perception-action, maximal boundary, affordance, climbing) were pooled (via Boolean operator "OR") and combined (Boolean operator "AND") with keywords relating to skill behaviour (i.e., calibration, attunement, perception, boundary, balance, novice, expert, elite, locomote, move) and also pooled by the Boolean operator "OR". Results were limited to those written about human participants, in English, and using the Web of Science, and PubMed databases. Google Scholar was then used to retrieve and examine all the eligible sources and the end text reference list of each article were also manually inspected for additional articles.

Restrictions were applied to the participant population, study design, and outcomes. Specifically, for inclusion, climbing studies were required to report expertise or experience of climbers, so that the ability level could be estimated. Study designs were limited to experimental or technical reports- so that perception, and balance parameters could be assessed for suitability. Sources must have included at least one measure of reach perception, or manipulations that influenced the capacity of perception or movement. Sources were appraised on their ability to contribute to understanding of how reach- and grasp-ness are perceived, and factors that affect how people perceive their action capabilities and movement.

2.2 Results

A total of 5663 sources were retrieved, with 231 identified and full-texts retrieved. After manual investigation of end text reference lists, a further 37 were included. After the removal of duplicate sources (n = 71), a total of 212 titles and abstracts were eligible for screening. To ensure source quality, the publication outputs of the remaining sources were crossed checked for indexing in the Thomas Reuter Journal Citation Report, where a total 6 journals (7 sources) were excluded. The remaining 205 sources were screened using the inclusion criteria, where 64 sources were excluded as they did not report climber experience or expertise. Of the remaining 141, 20 further sources were excluded for not fulfilling the secondary criteria of human participants, reach or grasp was not analysed, factors affection reach/grasp perception were not clear and the identified factors on movement were not stated, leaving 121 sources for further review (Figure 2).

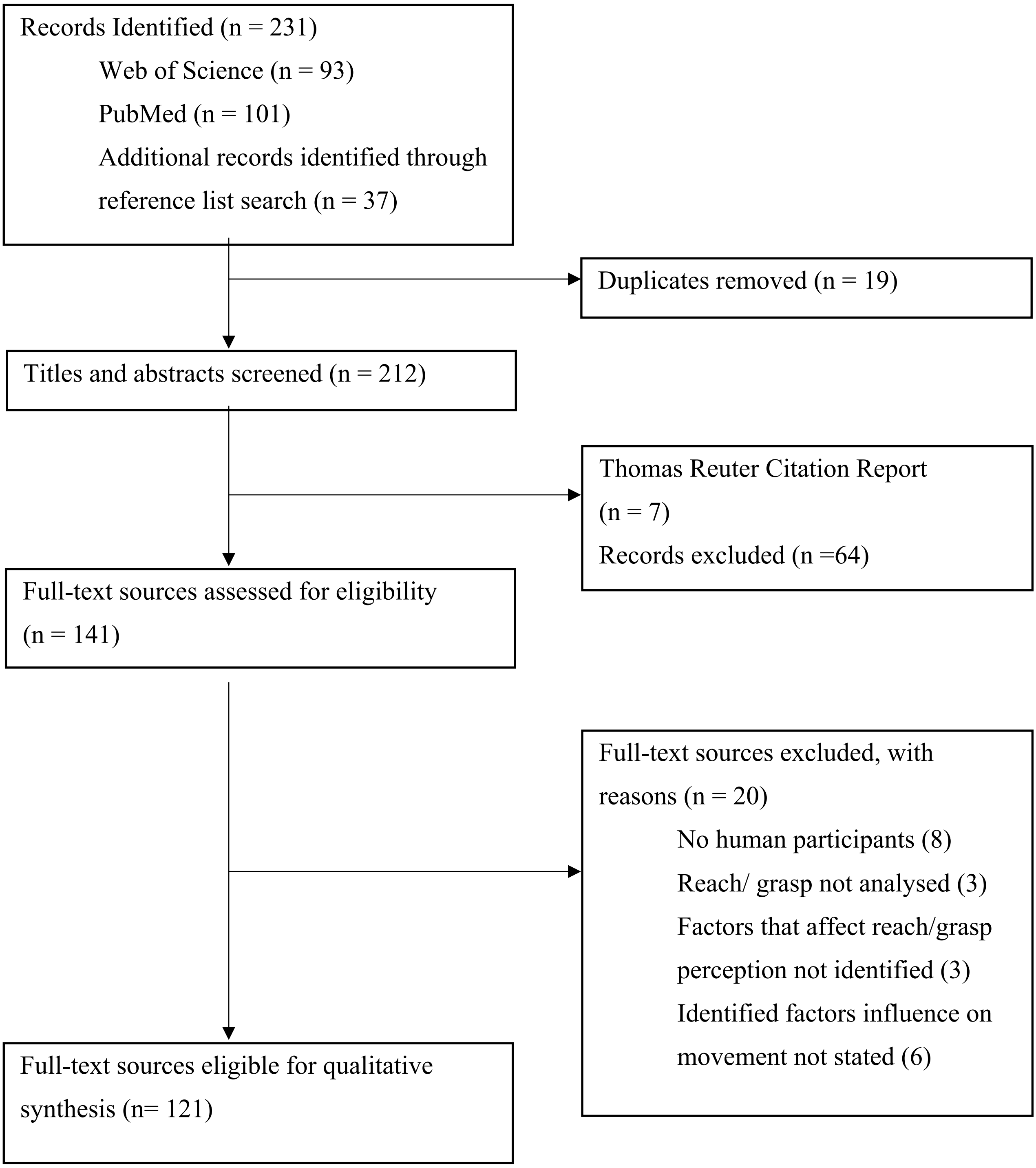

Figure 2. Flowchart of the selection process for the literature review

In line with Gibson's theory of affordances (1979), the literature review was structured into 3 categories: the perception of reach boundaries (the action). The second section will discuss environmental factors affecting reaching boundaries (the environment) and movement, and the third section will discuss organismic factors affecting reach boundaries (the animal). Moreover, the literature has been separated according to the perception of affordances and perception of geometric properties.

2.3 Perception of Affordances

Affordance perception is a prospective act - the actor needs to perceive how potential changes could influence affordances nested within the environment (Wagman, 2012; Wagman, Thomas, McBride, & Day, 2013). For example, if we are feeling tired (e.g. from wearing a backpack, fatigue) this may alter our ability to act, thus affecting how we perceive our affordances (Pijpers et al., 2007; Proffitt, Bhalla, Gossweiler, & Midgett, 1995). As many tasks are comprised of multiple sub-goals (see Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989), these prerequisite actions must be satisfied for an action to be realised (Stoffregen, 2003). For example, to pick up a glass, we must perceive whether the glass is reachable/graspable/usable: the distance to the glass, and how we will get there, the grasp that will be used and what we intend to do with it.

Similar to the perception of affordances, perceivers must understand how geometric properties (e.g. object height, width, etc.) affect their ability to act. Geometric properties resemble the physical properties of an object like a hammer or a mug (Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009). For example, a child's hand may not fit around the base of a mug therefore they are required to grasp its handle. Research shows that fatigue (Bhalla & Proffitt, 1999; Proffitt et al., 1995), object orientation (Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009), size (Bingham & Muchisky, 1993a), texture (Johansson & Westling, 1984), and task experience (Withagen & Michaels, 2005; Withagen & Van Wermeskerken, 2009) affects how people perceive geomtric properties. However, for a climber to achieve success, they must be able to accurately perceive affordances, geometric properties and how factos such as fatigue or encumbrance affect their perceptual accuracy.

If the task constraints change (e.g. foot movement is restricted while reaching), people are able to perceive such changes in reachability (Witt, Proffitt, & Epstein, 2005), but with decreased perceptual accuracy. For instance, while standing on a stool or using a stick, a group of participants estimated maximal reach as 89 to 93% of actual reach (Wagman & Morgan, 2010) compared to approximately 91% when standing on the ground and reaching with their hand. Perceptual accuracy often improves with brief experience (Hove, Riley, & Shockley, 2006), but the amount of experience is often unreported (Fischer, 2000; Pijpers et al., 2007). One study (Ramenzoni, Riley, Shockley, et al., 2008) that assessed perceived maximal jump height with and without ankle weights allowed participants to walk for 5 minutes to accommodate to their new capabilities. Perceptual estimates of their own maximal jumping reach height decreased in accordance with their actual capabilities, but accuracy did not improve (-16.0 cm pre-intervention versus -16.9 cm post-walking intervention). The lack of improvement may have been due to the type of experience (walking with weights around their ankles), which wasn't specific to estimating jump height or of sufficient duration to elicit changes in calibration.

To successfully execute an action, we must be able to differentiate between specifying and non-specifying information in the ambient array – a process called attunement. Specifying information directly relates to the perceived task on a one-to-one scale, whereas non-specifying information ambiguously relates to the perceived task (Withagen & Michaels, 2005; Withagen & Van Wermeskerken, 2009). For example, when asked to perceive the length of rods that were wielded but not seen, novices attuned to rod weight; however, rod weight is dependent on mineral composition and density, and thus it is a variant, non-specifying feature. With experience, perceivers attune to the specifying variable which in this experiment was the ratio of moment of mass distribution to mass (Withagen & Michaels, 2005). One difference between novices and experts is their different ability to attune to more specifying, less variant features (Abernethy, Gill, Parks, & Packer, 2001; Fajen, Riley, & Turvey, 2009; Hove et al., 2006; Weast, Shockley, & Riley, 2011). With practice and feedback, novices are able to converge to more specifying information sources (Jacobs & Michaels, 2006; Jacobs, Runeson, & Michaels, 2001; Michaels & de Vries, 1998). However, solely attuning to the specifying variable does not guarantee improved perceptual accuracy (Withagen & Michaels, 2005). Animals must also accurately calibrate capabilities to the desired task, a crucial component of understanding how we reach (Choi & Mark, 2004).

To make accurate movements, animals must also scale perceptual information to their action capabilities, a process called calibration (Fajen et al., 2009; For review see, van

Andel, Cole, & Pepping, 2017). In reaching tasks, calibration is measured by the perception of an observer's distance from an object and then comparing their estimates to their actual capabilities (Gardner, Mark, Ward, & Edkins, 2001; Pijpers et al., 2007). Physical and action capabilities can change slowly (e.g. age-related effects) or quickly (e.g. injury), so we must adapt accordingly. People recalibrate over a wide range of tasks, such as when walking with blocks on their feet (Mark, 1987), jumping and reaching while encumbered (Ramenzoni, Riley, Shockley, et al., 2008) or reaching using a tool (Day, Ebrahimi, Hartman, Pagano, & Babu, 2017; Witt et al., 2005). Accurate recalibration requires the presence of extrinsic feedback.

The accuracy of perceptual information changes depends on the type of task (Cole, Chan, Vereijken, & Adolph, 2013; Day, Wagman, & Smith, 2015). For many tasks where the object is static, such as picking up or moving a water bottle (Sartori, Straulino, & Castiello, 2011), perceptual accuracy is primarily constrained by the perceiver's physical properties (e.g. arm span). In locomotion tasks, such as climbing or leaping, perceptual accuracy is further constrained by the perceiver's dynamic properties (e.g. force production, balance) (Cole et al., 2013; Day et al., 2015). Because the information sources used to determine perceptual accuracy differ, comparing perceptual accuracy between the two types of tasks can be difficult. For example, participants' estimates fall within 2 to 3 cm when determining maximal vertical reach (Pepping & Li, 2005), but they underestimate their ability by 10 to 16 cm when asked to determine maximal jumping vertical reach (Ramenzoni, Riley, Davis, Shockley, & Armstrong, 2008; Ramenzoni, Davis, Riley, & Shockley, 2010).

2.4 The perception of reach boundaries

Reaching and grasping are fundamental to many daily activities and have been used extensively in research on affordances. Due to the range of activities afforded by reaching, reach- and grasp-ness can either be determined prior to movement (e.g. when mentally planning a climbing route) or emerge during movement (e.g. when making a reaching action). Tools, such as ice picks, extend the distance that someone can reach, and research has shown that people are capable of predicting how tools affect the limits of their reach (Witt & Proffitt, 2008; Witt et al., 2005).

Reaching movements can be classified into three categories: reach-, grasp-, and use-ness, and grasp-ness is often divided further into power and precision grips. Reach-ness reflects a person's ability to touch an object (Weast et al., 2011). Grasp-ness requires that the person be able to grasp the object using a grip/s that is/are appropriate for their intentions and the characteristics of the object (Fleming, Klatzky, & Behrmann, 2002). Whereas use-ness requires the person to use the grasped object in a way to satisfy an additional task goal (e.g. be able to grasp a climbing hold and use it to move to the next hold). In rock climbing competitions, the type of reaching affects scoring. The International Federation of Sport Climbing (IFSC) rules state that, "*a hold shall be considered as "controlled" where a competitor has made use of the hold to achieve a stable or controlled position, whereas a hold from which a competitor has made a controlled climbing movement in the interest of progressing along the route shall be considered as "used"*. To assist the judges with their decision, the IFSC rules clarify "*a controlled climbing movement may be either "static" or "dynamic" in nature and in general will be evidenced by (i) a significant positive change in position of the competitor's center of mass; and (ii) the movement of at least one hand in order to reach either the next hold along the line of the route*".

Healthy adults are proficient at determining their preferred and critical boundaries of reach (Mark et al., 1997), and grasp (Newell, Scully, Tenenbaum, & Hardiman, 1989) while seated. The critical boundary is the absolute physical limit a person can reach/grasp, whereas preferred boundary is the distance where a person transitions from one reaching/grasping action to another (Gardner et al., 2001; Mark et al., 1997). Early work investigating estimation of reach determined that physical limitations imposed by the task (e.g. whether the person was seated or standing) (Gardner et al., 2001) and the posture and comfort experienced during the action (Mark et al., 1997) influenced perceived reach. Biodynamic factors, such as hip flexibility and energy expenditure, affect perceived action capabilities of stair climbing (Konczak, Meeuwsen, & Cress, 1992; Warren, 1984), but few studies have investigated the influence of biodynamic factors on reach (Choi & Mark, 2004; Mark et al., 1997). These studies found that object distance, postural stability, weight and strength determined preferred reach actions (e.g. using arm and shoulder reach instead of arm only reach). Moreover, it has been suggested that factors like joint flexibility and how far a participant can lean may also influence preferred reach actions (Choi & Mark, 2004; Mark et al., 1997).

2.5 Environmental-based influences

A common environmental constraint that affects reach estimate is the grasp-ness of the object. Grasp-ness is influenced by many factors, such as object orientation (Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009), object size (Bingham & Muchisky, 1993a) and object texture (Johansson & Westling, 1984). Of these, object size has been studied the most (Bingham & Muchisky, 1993a, 1993b, 1995), and specifically, how the geometric size of the object affects the maximal size of the aperture between the thumb and fingers (Jeannerod, 1984). Object size does not always represent object grasp-ness, with some climbing holds being quite large but offering minimal of-use graspable surface (see Figure 3). Studies have shown that object size influences hand placement (Baud-Bovy & Soechting, 2001; Lederman & Wing, 2003; Sartori et al., 2011) and that participants typically exert force through the object's centre of mass (Lukos, Ansuini, & Santello, 2007; Lukos, Ansuini, & Santello, 2008).

Figure 3. Large climbing hold with minimal graspable surface

2.5.1 Perception of affordances

2.5.1.1 Object orientation

Changing an object's orientation can affect how a participant interacts with their environment (Seifert, Boulanger, Orth, & Davids, 2015; Seifert et al., 2014). Linkenauger, et al. (2009) presented participants with hammers in orientations that either facilitated or impeded grasp with their dominant and non-dominant hands. When hammers were more difficult to grasp, individuals estimated that they were farther away, and the contrary for hammers that were easier to grasp. While distance to the target location did not change, the authors stated that simply changing the orientation may have influenced the degree in which the tool could be reached using a functional grip. This is important in tasks such as indoor climbing, where hold orientation is commonly manipulated and affects how a climber grasps and moves – horizontal edge holds lead to significantly fewer exploratory and performatory movements and a higher climbing fluency than vertical and/or dual edge climbing routes (Seifert et al., 2015).

2.5.2 Perception of geometric properties

2.5.2.1 Object texture

Another attribute that may affect reach perception is object texture. If an object has a low coefficient of friction, a greater grip force is necessary to maintain support (Johansson & Westling, 1984). Thus, objects with lower coefficients of friction will need to be closer to prevent slipping. In rock climbing, a high coefficient of friction helps to maintain grip and prevent slipping. While climbers use chalk to dry out their hands, different rock types have different coefficients of friction (Li, Margetts, & Fowler, 2001). Lower coefficients of friction have been associated with greater task avoidance in children (Adolph, Joh, & Eppler, 2010), falls in adults (Cham & Redfern, 2002) and more precise finger placement when grasping objects (Fikes, Klatzky, & Lederman, 1994; Flatters et al., 2012). The coefficient of friction may not vary much with indoor climbing holds, but rock type and weather can affect the coefficient of friction for outdoor climbing.

2.6 Organismic influences on the perception of action boundaries

In rock climbing reach and grasp are affected by several organismic constraints such as strength, height, arm span, hand size and flexibility. For this review we were only interested in the effect of fatigue and encumbrance – constraints that can change within a session.

2.6.1 Perception of affordances

2.6.1.1 Task Experience

One factor that improves perceptual accuracy is task experience (Boschker & Barker, 2002; Hove et al., 2006). Athletes outperform non-athletes in perceiving domain-specific affordances (Weast et al., 2011). For example, expert hockey players were better than novices at differentiating which hockey sticks afford power or precision shots (Hove et al. (2006). Even non-experts are able to improve perceptual accuracy with increased task exposure (Abernethy et al., 2001; Weast et al., 2011). One potential explanation for the role of expertise in perceptual judgement involves attunement to specifying features (Abernethy et al., 2001; Weast et al., 2011). For example, Boschker, Barker, and Michaels (2002) found that after examining a climbing route, experienced climbers focused on functional aspects (moves) of a climb, whereas novices focused on structural / geometric aspects (holds). However, information sources to a perceived source depends on the constraints of the task (Runeson, 1988), thus changing task or discipline may require the participant to attune to different or additional information sources. For example, one should not assume that a highly skilled rock climber can transfer skill to ice-climbing.

2.6.1.2 Impact of balance for reaching

The relationship between balance and reach has been well-documented. Prior to reaching, participants make anticipatory postural adjustments to shift their centre of mass over their base of support to reduce postural disturbances associated with moving limbs (Bouisset & Zattara, 1981, 1987; Commissaris, Toussaint, & Hirschfeld, 2001; Stapley, Pozzo, & Grishin, 1998). Differences in postural control strategies have been reported between climbers and non-climbers when climbing up a wall (similar to a ladder climb), with climbers adopting a more diagonal movement pattern to maintain postural stability (Zampagni, Brigadoi, Schena, Tosi, & Ivanenko, 2011). In more difficult body positions (e.g. having two points of contact on the wall) or standing on a shorter surface (Horak & Nashner, 1986), balance can be harder to maintain; however, to date, limited work has investigated how the perception of maximal reaching capabilities are affected by anticipated postural perturbations in reaching while fatigued or when carrying additional load.

A seminal study by Mark et al. (1997) tested the effect of seated body position (upright, 28 degree backward lean, and 10 degree forward lean) and postural stability (ergonomic versus plywood chair) on participants' reaching behaviours. In this and related studies, perceptual estimates were expressed as a ratio of perceptual estimates to their actual capabilities, where a ratio of one indicates perfect estimation, less than one is an underestimation, and greater than one is an overestimation (Pepping & Li, 2000b). Mark et al. (1997) found that participants' preferred reach boundary was less in forward leaning (0.83), than upright (0.87) and backward leaning (0.96). The authors suggested that reach is affected by effort, energy expenditure and biodynamic efficiency (muscular strength, joint mobility, etc.). Relatedly, Gardner et al. (2001) investigated the influence of the task (threading of a bead or grasping a block) and comfort (partial or full standing) on reaching affordances. It was found that participants' preferred critical boundary was closer for the bead task (0.86) than the block task (0.94), with the transition between reach actions (ranging from arm only reach to full body reach) occurring at or around their perceived boundary of comfort, 0.84 and 0.93 of actual reach, respectively. These results suggest that when reach is unconstrained, transitions between reach actions (e.g. arm only reach to arm and shoulder reach) occurred earlier for tasks that require fine control (e.g. bead task), and that comfort experienced due to posture affects reaching affordances.

Fischer (2000) examined the influence of body position (standing versus laying supine), and stance (dual versus single leg stance) on reach estimates. Participants overestimated their reaching limit in standing by 17 mm and in lying supine by 10 mm. Furthermore, participants overestimated overhead reach (by 32 mm) and underestimated right-side reach (by 5 mm). Moreover, participants underestimated reaching limits more on the left side (by 39 mm) than the right side (by 32 mm). Reach estimates to the left differed depending on which leg they stood on: 36 mm when standing on the left leg, 34 mm standing on the right leg, and 37 mm when standing on both legs. It should be noted that participants in this study were right-hand dominant, and hand dominance has been reported to influence reach estimates (Linkenauger et al., 2009). This study would seem to be highly relevant to climbers who also reach sideways while in different stances. However, climbers have larger lateral centre of mass oscillations when in double foot support (Zampagni et al., 2011) than their non-climber counterparts in the same task. So, it is likely that differences will exist between climber and non-climbers' perception of horizontal reach capabilities when standing on one or two legs and whether their trunk faces the wall or sideways.

Participants underestimate their reach when balance is constrained (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Robinovitch, 1998), but there is debate to the underlying reasons. Balance may be influenced by one's ability to maintain centre of mass within their base of support (Carello et al., 1989; Robinovitch, 1998) or because participants perceive reaching with all available degrees of freedom despite instructions not to (Rochat & Wraga, 1997). To try and discern the reason, Fischer (2000) investigated the influence of the base of support (standing versus supine) and postural stability (dual versus one-legged stance) on horizontal and vertical reaching. For all conditions, participants were restricted to reaching only with their arm; their non-support foot rested on a board in the single-leg condition, restricting their ability to use it to counterbalance. The evidence suggested that a reach estimate is a multi-factorial problem that depends upon the participants' balance, the use of the whole body, and the location of the object to be reached for. Consequently, differences in reach estimates may be expected in activities like rock climbing where these factors are constantly changing when the climber moves through their environment.

2.6.1.3 Fatigue

Fatigue is one commonly used method to increase the energetic cost of movement. Pijpers et al. (2007) examined the influence of different fatigue levels on maximal overhead reaching affordances. They found that both perceived and actual maximal reach only decreased at high levels of fatigue (e.g. rating of perceived exertion 18-20 on a 20-point scale), suggesting a functional fit between perceived and actual capabilities; however, this study only examined left-handed reach. The authors noted small changes to the perceived reach height initially, which could have been due to the participant's inexperience as they attuned and calibrated to the task. Furthermore, maximal reach height was defined as the farthest distance a participant could hang from the assessment hold, meaning maximal distance could have been compounded by the participant's perceived ability to support themselves with their left hand.

Encumbrance

Adding weights to a person often displaces the position of centre of mass. Malek and Wagman (2008) found that when participants wore a weighted backpack on either their chest or back, their centre of mass shifted forwards or backwards respectively. This affected their perceived and actual capabilities of standing on an inclined surface. In both weighted conditions, participants underestimated their capabilities. However, they had limited exposure to wearing the weight. The authors suggested that prolonged exposure to the weights may have allowed them to become better attuned to their new capabilities, which may have resulted in greater accuracy (Higuchi, Takada, Matsuura, & Imanaka, 2004; Hirose & Nishio, 2001). Regia-Corte and Wagman (2008) suggest that consideration should be given to the height of the centre of mass when encumbering participants, as it can affect perceptual estimates. In their study, participants estimated standing height on an inclined surface with no additional mass, mass placed at their mid-back, and mass placed above the head. They found that a participant's perceptual boundaries changed significantly in accordance to the location of the additional mass. Participants perceived they could stand further up in the no-mass condition (30 degrees), followed by low (26 degrees) and high mass (25 degrees) locations. Participants underestimated their ability in the low and high mass condition, but not in the no-mass condition, suggesting that the participants had yet to reattune and recalibrate to new capabilities.

2.6.2 Perception of geometric properties

2.6.2.1 Fatigue

The link between fatigue and perceptual estimates has been documented by Proffitt and colleagues (Bhalla & Proffitt, 1999; Proffitt et al., 1995) who found that humans perceive environmental geometric features like hill slant as steeper distance or further when fatigued (e.g. after a long run). They suggest that people perceive their environment differently if there is an increased energetic cost (e.g. fatigued or encumbered) associated with the action. It has been argued that perception of distance is a function of both energetic effort and extent; reducing a participant's ability to produce force 'shrinks their perceptual ruler' causing something that was once perceived as attainable appear further away.

Examining the influence of fatigue on perceived geographical slant, Proffitt et al. (1995) asked 60 participants to judge hill slant prior to and after completing an exhausting run. They found that participants verbally overestimated hill slant by 35% after the run, but a motoric (haptic) estimation was relatively stable and accurate, suggesting that fatigue influences the participant's visual verbal cognitive pathway. A study by Bhalla and Proffitt (1999) further supported the findings of Proffitt et al. (1995) showing that participants verbally overestimated hill slant after an exhaustive run. Regrettably, neither study quantified the level of fatigue (exhausted or not), and the participant's ability to produce the action was not measured.

Despite the work on fatigue and perception by Proffitt and colleagues, its applicability to reach- and grasp-ness is limited and has been strongly criticised for experiment design (Durgin, Klein, Spiegel, Strawser, & Williams, 2012; Durgin et al., 2009). In their study, Proffitt et al. (1995) induced central fatigue before the perceptual estimates were provided. However, in climbing, the major cause of failure is peripheral fatigue in the hands and forearms (Watts, Daggett, Gallagher, & Wilkins, 2000), and emerges before, during and after the climber reaches for a hold. In climbing, fatigue can affect the climber's perception of affordances and geometric properties as the next movement or hold may seem too large. In climbing studies, many protocols have been used to induce fatigue including straight arm hangs (Watts et al., 2008), repetitive climbing (Pijpers et al., 2007) and isometric hangs. However, the impact of these protocols on climbing performance has yet to be quantified. While all of these protocols are relevant to climbing, there are inherent limitations. For example, hanging protocols requires climbers to be stationary, which only represents approximately one third of climbing time (Billat, Palleja, Charlaix, Rizzardo, & Janel, 1995). While repetitive climbing is more representative of the task, it can present a logistical issue: the route(s) need to be difficult enough that failure is induced by fatigue and not an inability to complete the route. Furthermore, such a methodology can be time consuming.

2.6.2.2 Encumbrance

Adding additional weight is method used to manipulate a person's energetic cost. By encumbering an individual, their mass and how it is distributed changes (Malek & Wagman, 2008). This causes balance and locomotion to be challenging (Adolph & Avolio, 2000; Bhalla & Proffitt, 1999) as the effort required to move increases (Proffitt, Stefanucci, Banton, & Epstein, 2003). Work by Bhalla and Proffitt (1999) and similar studies (Proffitt et al., 2003; Schnall, Harber, Stefanucci, & Proffitt, 2008) have shown that wearing a heavy backpack influences how people perceive geographical space. Bhalla and Proffitt (1999) found that encumbered participants produced greater overestimations than their unencumbered counterparts. However, participants only wore the backpack when giving estimates, preventing them from attuning and calibrating to their altered action capabilities. Caution should be exercised when applying the results for estimating spatial layout to the perception of action boundaries, as Proffitt and colleagues asked participants to estimate physical extents and not their ability to interact with the environment, thereby breaking perception-action coupling.

2.7 Conclusion

The aim of this review was to synthesise the current literature on the perception of reach- and grasp-ness and its impact on movement. Our results show that reaching, grasping and the interaction between these actions are complex tasks that are affected by a multitude of factors, from the orientation of the graspable surface, to the intended goal of the task. It is suggested that these above factors affect comfort level (Mark et al., 1997), energetic demand (Bhalla & Proffitt, 1999; Proffitt, 2006) and how they interact with their environment (Seifert, Boulanger, Orth, & Davids, 2015; Seifert et al., 2014). However, the majority of the research has focused on these factors in isolation. This approach generates a few potential concerns for a general understanding of the perception of reaching. Firstly, reaching and grasping have typically been treated as the main goal rather than part of a bigger goal (e.g. drinking water from a cup), arguably leading to a more analytical style of perceiving affordances, which does not always reflect how affordances are actualised (Heft, 1993). Moreover, it is likely that some factors may compound to affect perceptual estimates (e.g. fatigue and object orientation), whereas some may cancel (or reduce) the effect. Secondly, focusing on how a single factor affects reach- and grasp-ness can create a false dichotomy where it is assumed one variable is responsible for perceptual bias rather than the interaction of variables. Reaching and grasping are complex tasks, where the perception of action boundaries are influenced by a myriad of factors, therefore a more representative and holistic approach should be considered whereby the situation is examined and not the individual in isolation.

Perceptual inaccuracies are commonly reported in the literature, with participants overestimating reach (Carello et al., 1989; Pepping & Li, 2000b, 2008). Such inaccuracies may be due to participants perceiving reaching using their whole body, despite instructions not to (Rochat & Wraga, 1997), and their ability to maintain postural stability (Carello et al., 1989). While neither of these sufficiently account for perceptual inaccuracies, Fischer (2000) concluded that perceptual judgements might involve whole body simulation and the object position relative to the person when the reach is being performed - behaviours that have been associated with experienced climbers (Orth, Davids, & Seifert, 2016; Pezzulo, Barca, Bocconi, & Borghi, 2010). Despite this, limited research has examined whether climbers are more accurate than non-climbers at perceiving their reaching and grasping capabilities and how they relate to movement.

Perception of reach and grasp can be influenced by many factors, including fatigue, encumbrance, balance and stability. However, they have been examined in isolation and primarily investigations have focused on object manipulation (e.g. picking up or moving a glass). In more complex tasks, such as climbing, these factors likely interact, but there may be a ceiling effect because we are able to successfully reach in everyday activities (Choi & Mark, 2004) and similar daily tasks (Pepping & Li, 2000a).

CHAPTER THREE

The effect of expertise upon perceived horizontal reach- and grasp-ness in rock-climbers

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3.1 Abstract

Affordance perception is a forward-looking act, reflecting the individual's capacity to act within their environment. This is exemplified by experienced rock climbers who must determine how to reach, grasp and use a hold when balancing on one or both of their feet. The present study examined how base of support (single and dual leg balance) and hold size affects an individual's ability to determine their maximum boundary of reach- and grasp-ness. Maximal boundary of reach-to-support and reach-to-grasp was determined using a sliding assessment hold. 20 participants (n = 10 climbers; n = 10 non-climbers) provided estimates while perceiving themselves balancing on one or two feet and reaching for a big and small hold. Results showed a significant difference ($p = < 0.001$) in perceptual accuracy when perceiving maximal reach- and grasp-ness, however hold size and base of support did not. Moreover, no differences in perceptual accuracy could be found between climbers and non-climbers. Collectively, this study suggests how the perceiver planned to interact with the hold significantly affected the perception of action boundaries.

Keywords: Rock Climbing; Expertise; Perception

3.2 Introduction

In many sports, athletes reach for objects like catching a fly ball in baseball or cricket, or when hitting a forehand winner in tennis. Often, these skills are executed with such regularity that it is easy to overlook how participants determine if the desired object is reachable. In most tasks, the participants are relatively unrestricted from environmental constraints or obstacles. However, in rock climbing movements are constrained by the positioning of the climbing holds, and climbers must be able to reach and grasp holds while controlling the postural instability associated with limb movement (Bouisset & Zattara, 1987; Zampagni, Brigadoi, Schena, Tosi, & Ivanenko, 2011). Moreover, reach- and grasp-ness have been extensively studied, but these terms are often used interchangeably (Pijpers, Oudejans, & Bakker, 2007; Ramenzoni, Davis, Riley, & Shockley, 2010), which can present confusion in the literature. Reaching is often depicted as the maximal distance a person can cover with outstretched arms and fingers (Ramenzoni et al., 2010) whereas grasp reflects a person's ability to encompass an object with their fingers (Sartori, Straulino, & Castiello, 2011) - meaning an object may be within reach but not grasp.

In more difficult climbing routes, holds may be small, far apart, harder to grasp, and climbers are forced to hold more difficult postures. Experienced climbers are able to imagine themselves in these positions and often simulate climbing the route beforehand (Pezzulo, Barca, Bocconi, & Borghi, 2010). Experience allows climbers to correctly simulate more grip sequences (Pezzulo et al., 2010), suggesting simulation and route preview (Seifert, Cordier, Orth, Courtine, & Croft, 2017) improves climbing performance. While perceiving a sequence of grips is clearly important to climbing, it has not yet been addressed whether experienced climbers are more equipped to perceive the limits of their reach- and grasp-ness. Perceptual accuracy differs between groups of varying task experience in sport-specific tasks (Boschker & Barker, 2002; Boschker, Barker, & Michaels, 2002; Hove, Riley, & Shockley, 2006), but it is unclear how task experience affects perceptual accuracy when the perceived task is fundamental like reaching. Therefore, the purpose of this study is to examine if differences exist between novice and experienced climbers in terms of their perception of maximal reach- and grasp-ness.

Opportunities for behaviours, such as reaching for a climbing hold, are afforded or not by the environment (Gibson, 1979; Turvey, 1992; Wagman, 2008). Affordance perception is a personal, continual process shaped by one's development and experimental history

(Pijpers et al., 2007; Higuchi et al., 2011; Seifert et al., 2014). Therefore, what one climber perceives as an affordance may not be perceived by another climber. Accumulated experience of a task may help the perceiver to attune to specifying information that directly relates on a one-to-one scale with the perceived property for action – called attunement (Withagen & Michaels, 2005; Withagen & Van Wermeskerken, 2009). Moreover, task experience may assist the perceiver scale their capabilities to the task – a process known as calibration (Fajen, Riley, & Turvey, 2009). Calibration can be measured by using two metrics: body- and action-scaled affordances. Body-scaled affordances describe the relation between the perceiver's body (e.g. arm span) to the property in the environment, whereas, action-scaled affordances define how the perceiver behaves (e.g. jump reach height) relative to their environment (Fajen et al., 2009). Together, improved attunement and calibration allow for enhanced perceptual accuracy. However, in static perceptual judgement tasks, participants overestimate reach by 5 to 10 cm (Pijpers et al., 2007).

The importance of task experience for perceptual accuracy has been well-documented for a range of tasks such as climbing and hockey (Boschker & Barker, 2002; Hove et al., 2006). Research shows that experts outperform novices in determining which hockey sticks afford power or precision shots – through haptic exploration (Hove et al., 2006), or which aspects of a climbing route to focus on through visual exploration (Boschker et al., 2002). Exposure to a few trials may improve perceptual accuracy (Pijpers et al., 2007), although the optimal duration of this exposure is unknown and is not often reported (Fischer, 2000). Recently, rock climbing has been used to examine how people perceive maximal reach-and-grasp (Pijpers et al., 2007; Pijpers, Oudejans, Bakker, & Beek, 2006). These studies found that participants with limited task experience underestimate their maximal boundary of overhead grasp.

Postural stability in rock climbing prior to, during and after the grasp is a primary determinant of success (Bourdin, Teasdale, & Nougier, 1998). By releasing a hold, the climber removes an anchorage point, creating a postural disturbance (Bouisset & Zattara, 1987) and a less stable equilibrium (Quaine, Martin, & Blanchi, 1997). On a vertical wall, displacing a limb from the wall increases the forces applied to the contralateral side by 12 to 58 N (Quaine & Martin, 1999). Fischer (2000) found no significant difference between perceived reach estimates when in a single or dual leg support; however, in the single leg condition participants rested their non-support leg on a board, which minimised changes in stability. By having the participants rest their leg on a board, their ability to reorganise their multiple degrees of freedom to safely control their centre of mass was limited. Therefore, they may not have been able to engage in a maximal full body reach. As climbers commonly engage in single leg full body reaching, understanding how postural stability affects the perception and actualisation of maximal reach- and grasp-ness is important.

When climbing a route, climbers reach for and grasp holds of different shapes; in more difficult climbs the graspable surface is more ambiguous. Previous research has established that the size of the object's graspable feature (e.g. handle) affects a person's finger placement (Sartori et al., 2011) and perceived distance to it (Linkenauger, Witt, & Proffitt, 2011; Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009). For example, a hammer was perceived farther away when the graspable feature was rotated away from the participant, even though the overall distance did not change (Linkenauger et al., 2009). One limitation with the current body of literature as in this previous study is that many of the objects have obvious graspable features, which is not always the case for climbing holds.

Reaching is a complex action that is affected by a multitude of factors including object size and base of support. Many studies have employed everyday functional tasks like reaching for bottles or hammers. There is a growing body of research examining how people perceive reach and grasp in climbing, but many of the participants are inexperienced, and perceive overhead reach without having to imagine how the body can be reconfigured to optimise reach. Therefore, the aim of this study was to investigate the influence of climbing experience on the maximal perception of reach- and grasp-ness for different body positions and hold sizes. We hypothesised that perceived reach would be more accurate for climbers than non-climbers and that both hold size and body position would affect the accuracy.

3.3 Methods

3.3.1 Participants.

Based on previous research (Pezzulo, Barca, Bocconi, & Borghi, 2010; Seifert et al., 2018), ten climbers (7 males, 3 females) and ten non-climbers (10 males), aged 16 to 45 years, volunteered to participate in the experiment. Moreover, given the inclusion criteria (expertise) it was difficult to get more participants within the Perth area. The climbers were rated intermediate or above (ie., +22 on the Ewbank climbing difficulty scale) with a minimum of 24 months experience. The non-climbers had no prior climbing expertise either competitively or recreationally. All participants were healthy and injury free at the time of testing. Prior to the study participants signed a written informed consent, with approval provided by the participating institution's Human Ethics Committee. For the testing they wore sport clothing with comfortable climbing shoes, and a climbing harness.

3.3.2 Experimental setup.

Participants attended two testing sessions of approximately 90 minutes duration, separated by a minimum of one day. For this study, the maximal boundary of reach-to-support was defined as the maximal distance where the participant could lean against the side of the assessment hold for 3 s; maximal boundary of reach-to-grasp was defined as the maximal distance where the participant could grip the assessment hold with their hand for 3 s. For both types of reach (touch, grasp), the participants were told to imagine that their subsequent movement would be to move the foot towards the middle of the wall, even though no hold was present (see Figure 4).

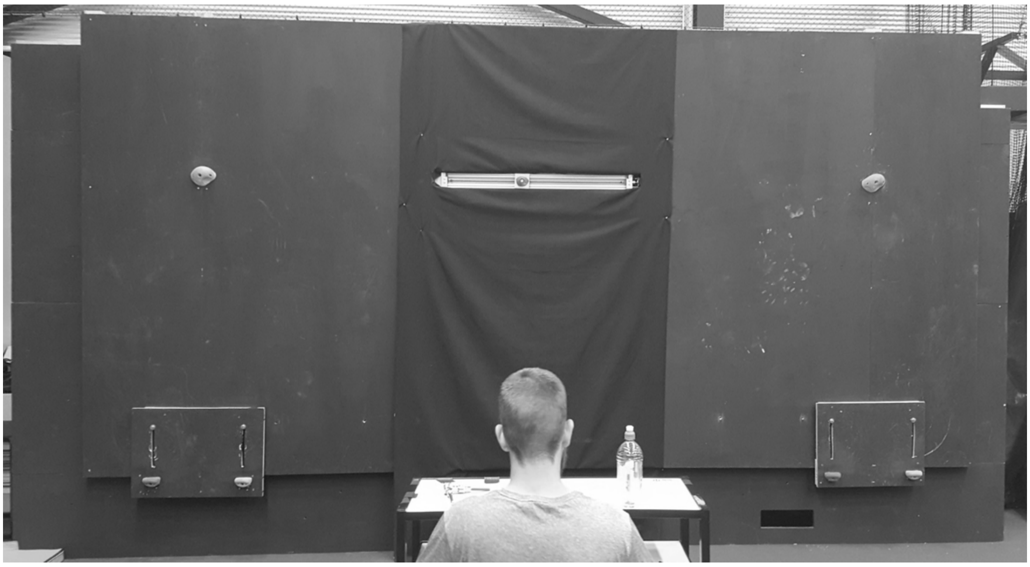

Figure 4. Experimental Setup with examiner (seated)

Similar to the work of Pijpers et al. (2007) the assessment holds, were attached to a horizontal sliding mechanism (that could move a distance of 97 cm) constructed using a ball screw and a stepper motor controlled by an Arduino (Interactive Design Institute, Ivrea, Italy). The sliding mechanism was placed 120 cm from the starting hand hold. A joystick allowed the experimenter to move the hold horizontally at a fixed speed of 2 cm/s. To hide any reference points, the sliding mechanism was mounted flush with the climbing wall and the wall was painted black. Furthermore, a black curtain was placed over the middle section of the wall, with a channel cut so the sliding mechanism was visible.

Participants estimated their maximal static horizontal reach-to-support and reach-to-grasp (for details see Procedure) while standing with both feet on two-foot holds (see Figure 4). The foot holds were attached to separate wooden panels, and the height of the panels was adjustable, such that the participant's acromion process could be placed in line with the middle of the horizontal sliding mechanism. The participant gave three perceptual estimates on each side of the wall (i.e. reaching to the left and reaching to the right) for two conditions: 1) body position (dual and ipsilateral leg support), and 2) hold type (big and small)

Participants provided three perceptual estimates for reach- and grasp-ness for both hands for each condition, totalling 48 estimates for each session (3 estimates x 2 hands x 2 reach modes x 2 holds x 2 body positions; Figure 5). For each session, the conditions were counterbalanced; however, the order of the conditions were randomised. The participants placed both feet on two foot holds 46 cm apart (see Figure 4). The foot holds were attached to separate wooden panels, and the height of the panels was adjusted so the acromion process of each participant was aligned with the middle of the horizontal sliding mechanism.

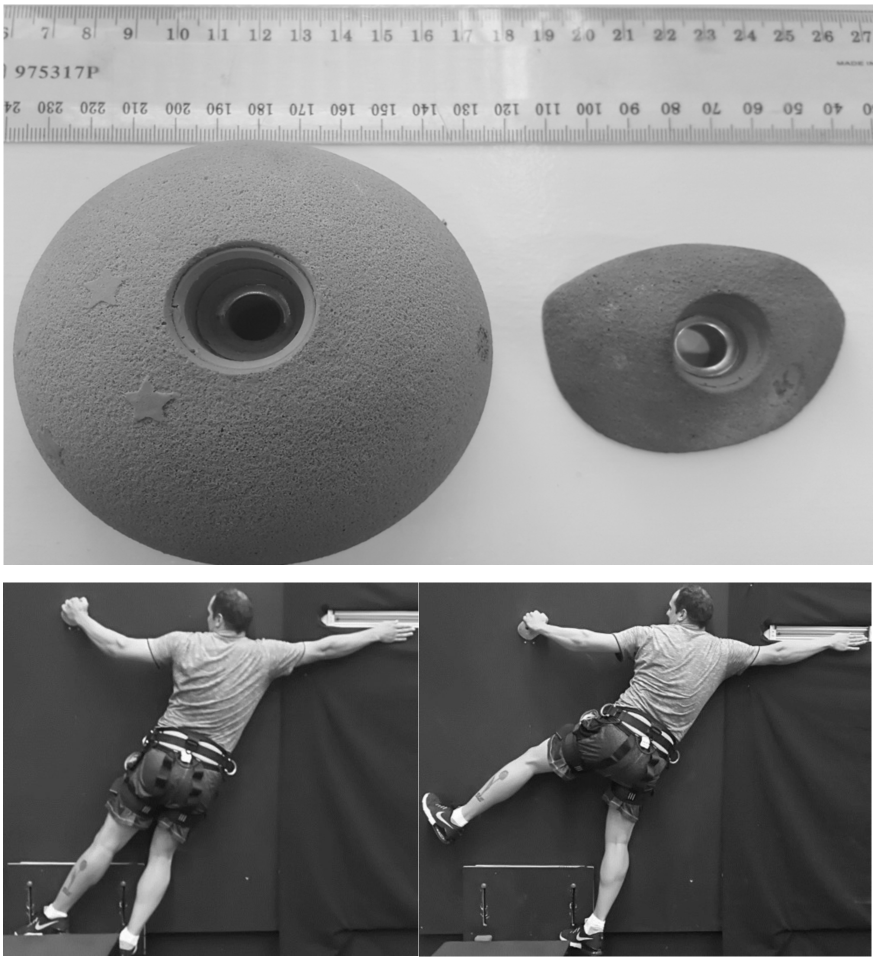

Figure 5. Hold sizes and body positions. From left to right, top to bottom (a) big hold, (b) small hold, (c) dual leg reach, (d) single leg reach.

For the first estimate, the assessment hold was placed at the end of the sliding mechanism closest to the participant. For subsequent estimates, the assessment hold was randomly placed either side of their previous estimate at 10, 15, or 20 cm intervals. The participant told the investigator when to stop the sliding mechanism and they were allowed to make as many corrections until they were satisfied. When the participants signalled for the sliding mechanism to stop, they were prompted with "closer or further?" by the investigator until the participant stated they were happy and stepped off from the foot holds. The distance along the slide was measured using a tape measure out of sight of the participant.

3.4 Procedure

During each testing session, participants wore a harness and stood in a standardised position on the portable climbing wall. For the standardised position, participants were required to have both feet on the foot holds at all times and to hold a fixed hold with their non-assessment hand, keeping their assessment hand by their side. Prior to getting on the wall, the participants were instructed of the posture in which they were to perceive (e.g. dual leg reach with the right hand). Once the participants were on the wall in the standardised position, the sliding hold was moved by the chief investigator using a joystick.

When the participant was satisfied with the placement of the assessment hold, they stepped down from the wall and walked behind a screen to ensure they could not see the wall. During this time, the investigator measured and recorded the distance of the assessment hold. Reach-to-support estimates were measured from the middle of the fixed hold to the near side of the assessment hold. Grasp estimates were taken from the middle of the fixed hold to the middle of the assessment hold (Lukos, Ansuini, & Santello, 2007; Lukos, Ansuini, & Santello, 2008). The position of the assessment hold was then reset for the next trial, and the participant was instructed to re-enter the testing area. Each trial and the starting position of the assessment hold were presented in a random order.

At the end of the second session, once the participants had completed all of the perceptual estimates, their actual maximum reach-to-support and reach-to-grasp assessments were recorded. The assessment hold was moved to the side of the mechanism where the participant either placed their fingers against the side of the hold (reach-ness) or grasped the hold (grasp-ness). When the participants were in the correct position, the assessment hold was moved until the participant started to fall off. From there the hold was brought closer until participant said "stop". They maintained contact with the hold for at least 3 s to ensure they could fulfil the reach- and grasp-ness criteria. After the 3 s, participants were asked closer or further until they were happy. If re-adjustments were made, the participants were required to maintain contact with the hold for 3 s. This was repeated for both hands, hold sizes, and body positions. The participants provided one actual maximal assessment for each condition.

3.5 Data Analysis

A π (Pi) number was calculated as the ratio of perceived and actual maximal horizontal reach- and grasp-ness (Pepping & Li, 2000). Values under 1 indicated an underestimation, values greater than 1 were an overestimation, and a value of 1 reflect perceptual judgements that exactly reflect action capabilities (Croft, Pepping, Button, & Chow, 2018). To determine if perceptual estimates are body scaled, a secondary Pi number (π_2)

was calculated as the ratio between perceived horizontal reach- and grasp-ness and arm-span. All statistical analyses were conducted using the lme4 (Bates, Mächler, Bolker, & Walker, 2014) and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017) packages in the R statistics program (R Core Development Team, 2016).

To understand how object size and base of support affected the perception of maximal reach and grasp between climbers and non-climbers, we constructed linear mixed effect models using binary predictors of experience and reach mode. We modelled the interaction between experience and reach modes (Model 1: π ~ expertise * mode + (1|Hold) + (1|Body) + (1|ID)) and additive effect of experience and reach modes (Model 2: π ~ expertise + mode + (1|Hold) + (1|Body) + (1|ID)) on the maximal perception of action boundaries for both hold sizes and body positions using linear mixed models. The same procedures were followed to determine the effect of object size and support of support on body scaled estimates (Model 3: π_2 ~ expertise * mode + (1|Hold) + (1|Body) + (1|ID)) and additive effect of experience and reach modes (Model 4: π_2 ~ expertise + mode + (1|Hold) + (1|Body) + (1|ID)). Coefficients for both body and hold variables were examined to see how much variation they accounted for in the π values. Based on these results, non-contributing factors were removed from the final model. Significance was set at an alpha level of $p \leq 0.05$.

3.6 Results

Both climbers and non-climbers' perceptual accuracy was not significantly affected by hold size, base of support, and expertise, whereas significant differences were found when changing between reach modes. Overall, both climbers and non-climbers provided more accurate estimates for their action-scaled reach-to-grasp affordances; however, reach-to-support was more accurate when examining their body-scaled affordances.

Perceptual judgement of action boundaries for reach and reach-to-grasp

Non-climbers tended to underestimate their maximal reach (Table 1) and reach-to-grasp (Table 2). Only one non-climber overestimated reach-to-grasp boundary (left hand, single leg, small hold). In contrast, climbers were relatively accurate perceiving their maximal boundary of reach (Table 1) but overestimated the maximal boundary of reach-to-grasp (Table 2).

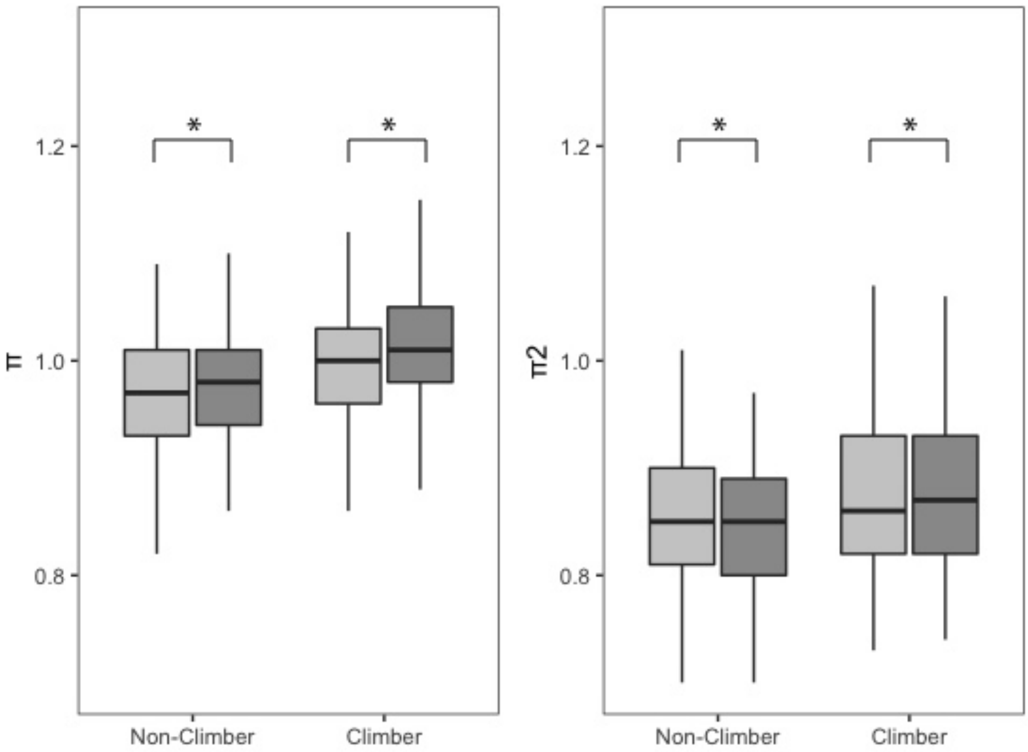

Figure 6. Perceived-actual (π) and body-scaled (π2) ratios for climbers and non-climbers for reach (light grey) and grasp (dark-grey) respectively.

Table 1.Perceived-actual ratios for reach for each hand between climbers and non-climbers for base of support and hold size (means ± sd)

	Climbers				Non-Climbers			
	Dual-leg		Single-leg		Dual-leg		Single-leg	
	Big	Small	Big	Small	Big	Small	Big	Small
Left	0.99 ± 0.06	1.00 ± 0.05	1.02 ± 0.04	1.03 ± 0.06	0.97 ± 0.06	0.96 ± 0.05	0.99 ± 0.05	1.00 ± 0.06
Right	0.98 ± 0.06	0.96 ± 0.06	1.01 ± 0.06	0.99 ± 0.05	0.93 ± 0.04	0.94 ± 0.05	0.96 ± 0.05	0.96 ± 0.06

Table 2. Perceived-actual ratios for grasp for each hand between climbers and non-climbers for base of support and hold size (means ± sd)

	Climbers				Non-Climbers			
	Dual-leg		Single-leg		Dual-leg		Single-leg	
	Big	Small	Big	Small	Big	Small	Big	Small
Left	1.03 ± 0.06	1.04 ± 0.06	1.05 ± 0.06	1.07 ± 0.06	0.97 ± 0.04	0.98 ± 0.04	0.99 ± 0.04	1.01 ± 0.04
Right	1.01 ± 0.06	1.00 ± 0.06	1.04 ± 0.06	1.04 ± 0.05	0.94 ± 0.03	0.95 ± 0.05	0.96 ± 0.04	0.97 ± 0.05

Expertise did not account significantly affect the participants perception of maximal horizontal capabilities ($F_{(1,\ 20)} = 3.54$, $p = 0.07$); however, when controlling for experience across climbers and non-climbers, reach mode showed a significant effect ($F_{(1,1898)} = 5.97$, $p = 0.01$). The coefficients for hold and body position revealed that neither variable accounted for variation in reach/grasp accuracy. However, there is an interaction of experience and mode, suggesting that for climbers, reach mode is more predictive of π accuracy (Model: π ~ expertise * mode + (1|ID). Moreover, reach action significantly affected the participant's perception of maximal horizontal capabilities ($F_{(1,1898)} = 47.80$, $p = < 0.001$) with reach-to-grasp resulting in larger and generally more accurate perceptual estimations than reach condition.

Perceptual judgement of body scaled boundaries for reach-to-support and reach-to-grasp

Comparing the ratios between climbers and non-climbers, both groups tended to underestimate their maximal reach (Table 3) and reach-to-grasp (Table 4); however, climbers provided more accurate estimates for every condition.

Table 3. Body scaled ratios for reach base of support and hold size conditions for climbers and non-climbers (means ± sd)

	Climbers				Non-Climbers			
	Dual-leg		Single-leg		Dual-leg		Single-leg	
	Big	Small	Big	Small	Big	Small	Big	Small
Left	0.88 ± 0.08	0.87 ± 0.08	0.92 ± 0.08	0.91 ± 0.07	0.84 ± 0.06	0.84 ± 0.05	0.88 ± 0.07	0.88 ± 0.06
Right	0.85 ± 0.08	0.87 ± 0.08	0.89 ± 0.08	0.91 ± 0.07	0.82 ± 0.06	0.82 ± 0.05	0.85 ± 0.07	0.85 ± 0.07

Table 4. Body scaled ratios for grasp for base of support and hold size conditions for climbers and non-climbers (means ± sd)

	Climbers				Non-Climbers			
	Dual-leg		Single-leg		Dual-leg		Single-leg	
	Big	Small	Big	Small	Big	Small	Big	Small
Left	0.89 ± 0.08	0.87 ± 0.07	0.93 ± 0.08	0.91 ± 0.07	0.84 ± 0.05	0.84 ± 0.05	0.88 ± 0.06	0.86 ± 0.05
Right	0.85 ± 0.08	0.86 ± 0.08	0.90 ± 0.08	0.90 ± 0.07	0.82 ± 0.06	0.81 ± 0.05	0.84 ± 0.07	0.84 ± 0.05

The participants perception of maximal horizontal capabilities was not affected by their expertise ($F_{(1, 20)} = 2.38$, $p = 0.13$). When controlling for experience across climbers and non-climbers, reach mode also showed a significant effect ($F_{(1,1898)} = 10.89$, p = < 0.001). The coefficients for hold and body position revealed that neither variable accounted for variation in reach/grasp accuracy. However, there is an interaction of experience and mode, suggesting that for climbers, reach mode is more predictive of π accuracy (Model: π_2 ~ expertise * mode + (1|ID). Moreover, reach mode significantly affected the participant's perception of maximal horizontal capabilities ($F_{(1,1898)} = 4.92$, p = < 0.02) larger and more accurate perceptual estimates provided when perceiving reach-to-grasp.

Effect of hold size

For body-scaled capabilities, 10 non-climbers (100% of the sample) and 9 climbers (79% of the sample) showed a consistent underestimation of their abilities, with only 1 climber (climber #1) deemed to be an accurate estimator. In contrast, 3 non-climbers (30% of the sample), and 1 climber (10% of the sample) were judged to be under-estimators, with 3 non-climbers (30% of the sample) and 3 climbers (30% of the sample) deemed to be consistent accurate estimators of their action capabilities for both big and small holds.

Changing task expertise did significantly affected the participant's perceptual accuracy of their maximal horizontal action capabilities ($F_{(1,1917)} = 10.84$, $p = 0.001$). Moreover, differences in reach mode did significantly affected the participant's perceptual accuracy of their maximal horizontal action capabilities ($F_{(1, 1915)} = 26.96$, $p < 0.0001$). When controlling for experience across climbers and non-climbers, reach mode did not show a significant effect ($F_{(1,1915)} = 3.36$, $p = 0.06$), on the participant's perceptual accuracy.

Effect of body position

For body-scaled affordances, 9 non-climbers (90% of the sample) and 9 climbers (90% of the sample) consistently underestimated their abilities, with only 1 climber (climber #1) deemed to be an accurate estimator. In contrast, 2 non-climbers (20% of the sample) consistently underestimated, and 1 climber (10% of the sample) consistently overestimating their action-scaled capabilities. Overall, 5 non-climbers (50% of the sample) and 4 climbers (40% of the sample) consistently estimated their action capabilities accurately.

Changing task expertise did not significantly affected the participant's perceptual accuracy of their maximal horizontal action capabilities ($F_{(1,1917)} = 0.61$, $p = 0.43$); however, differences in reach mode did significantly affected the participant's perceptual accuracy of their maximal horizontal action capabilities ($F_{(1, 1915)} = 30.64$, $p < 0.0001$). When controlling for experience across climbers and non-climbers, reach mode did not show a significant effect ($F_{(1,1915)} = 3.83$, $p = 0.0502$), on the participant's perceptual accuracy.

3.7 Discussion

The present study investigated the influence of experience on the maximal perception of reach- and grasp-ness for different body positions and hold sizes. The main finding was that the intention to reach-to-support or reach-to-grasp the hold significantly affected the participant's perception of action- and body-scaled boundaries. Secondly, expertise did not contribute to the perception of action boundaries. Despite this result, climbers did provide more accurate estimates when normalised to arm-span. Together, these results suggest that the intended action (reach-to-support or reach-to-grasp) affects perceptual accuracy, but surprisingly not climbing experience. Additionally, changes to body position and hold size did not account for any significant variation in the model used to assess reach accuracy. The results of this study support our hypothesis that changes between reach actions affect perceptual accuracy; however, factors such as body positing and hold size did not.

Effect of reach mode on perceptual accuracy

Our results suggest that the manner in which a person interacts with an object can affect how they calibrate their maximal horizontal boundary of reach- and grasp-ness. Previous research has shown that people can determine in advance how they are going to grasp and use an object (Lukos et al., 2007; Lukos et al., 2008; Sartori et al., 2011) and calibrate reach distance to the objects functional feature (Linkenauger et al., 2009). The non-climbers' conservative body-scaled estimates could have been limited by their ability to balance on the climbing hold and reconfigure their centre of mass to prevent falling. Contrary to instructions, it could be possible that climbers perceived moving dynamically towards the hold prior to reaching and grasping – extending how far they would be able to reach and grasp.

Is experience a contributing factor to perceiving reach- and grasp-ness?

The results suggest that task experience was not a significant contributing factor when determining horizontal reach- and grasp-ness. While studies have found that task experience is significant in predicting the perception of affordances (Boschker & Barker, 2002; Hove et al., 2006), the novice participants were perceiving novel specialised sport skills. In our study, the participants were asked to perceive a fundamental action that may be performed frequently each day (Choi & Mark, 2004), and the participant's task experience was only judged on their years of climbing experience. One alternate interpretation of these results could be that the differences between hold shape was insufficient to change the task complexity. It is possible that the holds used in this study shared similarities with everyday objects (e.g. fruits, tools) - reducing the task complexity. It is likely that using climber specific holds (e.g. featureless holds like slopers) would increase task complexity, as perceivers would need to attune to different information to be perceptually accurate.

Currently, most of the reaching literature has focused on overhead and horizontal frontal reach- and grasp-ness (Mark et al., 1997; Pepping & Li, 2000, 2008; Pijpers et al., 2007). Not much attention has been paid to maximal horizontal reach- and grasp-ness (Croft et al., 2018). Our results on maximal reach-ness are comparable to those of Croft et al. (2018) who found children underestimated maximal horizontal reach-ness. From a practical perspective, horizontal reach- and grasp-ness is important for climbers who are frequently required to make extreme reaches and grasps. Our results suggest that climbers should be more accurate at determining their maximal horizontal action-scaled boundary of reach (1.01 for climbers and 0.97 for non-climbers) and their maximal horizontal body-scaled boundary of reach and grasp. Moreover, both climbers and non-climbers were equally accurate at perceiving their maximal horizontal action boundary of grasp (1.02 for climbers and 0.98 for non-climbers). However, participants were required to maintain contact with both hand holds which could have possibly affected how their grasped the target hold.

3.8 Limitations

Arguably, the methodology used in this study was limited as the participants were perceiving unsupported reach- and grasp-ness; however, during the actualisation protocol the participants remained in contact (supported) with the assessment hold. We acknowledge that this design may have limited the sensitivity or validity of the measurements. While some research has asked the participants to stop the assessment object and immediately reach for it (Pijpers et al, 2007), we believe that employing this methodology would have presented numerous challenges. From a pragmatic standpoint, rock-climbers often dynamically reach for a hold, using their opposing leg for a counterbalance when a hold is near their maximal action boundary – resulting in many repeated actualisations. If the participants were to continually reach and grasp for the hold, it is possible that the sliding mechanism would have been damaged or broken.

3.9 Conclusion

In this study, we examined the influence of expertise on the maximal perception of reach- and grasp-ness for different body positions and holds sizes. Overall, both climbers and non-climbers were reasonably accurate in perceiving their action boundaries. Three important findings have emerged from this study. First, the manner in which the perceiver interacts with the hold significantly affected the perception of action- and body-scaled boundaries. Secondly, expertise did not contribute to the perception of action boundaries. Finally, expertise was a significant contributor to perceptual accuracy in the hold size condition once the participants were classified into under-, accurate and over-estimators. It is recommended that future studies examine how biodynamic factors native to climbing, such as additional load, and fatigue affect the perception of reach- and grasp-ness.

CHAPTER FOUR

The effect of additional load and fatigue on perceived reach- and grasp-ness of rock climbers

Walsh, A. S.[1], Seifert, L.[2], Button, C.[3], Croft, J. L.[1]

4.1 Abstract

Affordance perception is dynamic, reflecting the individual's capacity to move purposely within their environment . This is exemplified by experienced outdoor rock climbers who must determine how to reach, grasp and use a hold when fatigued and carrying safety gear. The present study examined how carrying an additional load and the accumulation of fatigue affects an individual's ability to determine their maximum boundary of reach- and grasp-ness. Maximal boundary of reach-to-support and reach-to-grasp was determined using a sliding assessment hold. 19 participants (n = 10 climbers; n = 9 non-climbers) provided estimates while carrying 10% body mass (BM) around their hips or shoulders. Participants then performed 12 isometric hangs until voluntary termination with no weight or carrying 10% BW around their hips, with estimates provided after each hang. Results showed a significant ($p = < 0.001$) difference in perceptual accuracy when perceiving maximal reach- and grasp-ness, whereas fatigue, load, load position and expertise did not. The results suggest how the perceiver planned to interact with the hold significantly affects how they perceive their action boundaries.

Keywords: Rock Climbing; Expertise; Perception; Fatigue

4.2 Introduction

In rock climbing, climbers reach for and grasp climbing holds to move through their environment. When a climber releases a hold to move, a postural instability is created (Bouisset & Zattara, 1987; Zampagni, Brigadoi, Schena, Tosi, & Ivanenko, 2011) causing balance to be more difficult to maintain – affecting their ability to reach (Fischer, 2000). While reach- and grasp-ness have been studied extensively, these terms are often used interchangeably (Pijpers, Oudejans, & Bakker, 2007; Ramenzoni, Davis, Riley, & Shockley, 2010) and this can present much confusion in the literature. Reaching describes the distance a person can cover with an outstretched arm and fingers (Ramenzoni et al., 2010), whereas grasping depicts the person's ability encompass an object with their fingers (Sartori, Straulino, & Castiello, 2011) – meaning an object can be reachable but not graspable.

When climbing outdoors, postural stability can be harder to maintain as climbers typically carry an assortment of safety gear, the nature and weight of which can vary according to climber preference and route length (loads of up to 7.5kg are not uncommon). Carrying additional weight can affect a person's perceived and actual capabilities (Bhalla & Proffitt, 1999; Malek & Wagman, 2008; Proffitt, Stefanucci, Banton, & Epstein, 2003; Regia-Corte & Wagman, 2008). Furthermore, outdoor climbers have limited opportunities to rest when climbing, often resulting in climbers continuing to climb while experiencing high levels of local muscular fatigue so they can reach a safe place on the wall to rest. Local muscular fatigue also affects perceived and actual capabilities (Bhalla & Proffitt, 1999; Pijpers et al., 2007). The combination of fatigue and carrying extra load, may compound errors of perceptual estimates (Ramenzoni, Riley, Shockley, & Davis, 2008). Moreover, carrying additional load and experiencing fatigue is argued to increase the energetic cost of movement (Bhalla & Proffitt, 1999; Proffitt, 2006), thus affecting how people perceive their environment (Bhalla & Proffitt, 1999; Proffitt et al., 2003). Perceptual accuracy differs between groups of varying task experience in sport specific tasks (Boschker & Barker, 2002; Boschker, Barker, & Michaels, 2002; Hove, Riley, & Shockley, 2006), but it is unclear how task experience affects perceptual accuracy when the perceived task is fundamental like reaching and grasping. Therefore, the purpose of this study is to examine the influence of carrying additional weight, the location of the weight and fatigue on perceiving maximal horizontal reach- and grasp-ness for climbers and non-climbers.

According to Gibson (1979) a perceiver's opportunities for actions (e.g. whether an object is reachable or not) are invited by the environment – a concept called "affordances" (Turvey, 1992; Wagman, 2008). Affordances are shaped by the perceiver's previous (Pijpers et al., 2007), present experiences (Higuchi et al., 2011), and person capabilities (Seifert et al., 2014). A perceiver's capabilities can change over long (e.g. age-related effects) and short (e.g. carrying additional weight or fatigue) time scales, affecting their ability to act (Pijpers et al., 2007). Task experience helps the perceiver to attune (Withagen & Michaels, 2005; Withagen & Van Wermeskerken, 2009) and calibrate their action capabilties to the task (Fajen, Riley, & Turvey, 2009). Together, improved attunement and calibration allow for enhanced perceptual accuracy; however, inaccuracies are still commonly reported in reaching studies (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Pepping & Li, 2000, 2008).

When a person carries additional weight, their ability to accurately perceive their environment is potentially disrupted. Seminal work by Bhalla and Proffitt (1999) showed that participants encumbered with a heavy backpack - one fifth to one sixth of body mass - were less able to perceive hill slant than when unencumbered. In addition, Ramenzoni et al. (2008) found that participants who carried 5% of their body mass around their ankles underestimated their maximal jump height but their perceived estimates appeared to change in line with their actual jump height. Taken together, these results suggest that carrying additional weight affects affordance perception (Bhalla & Proffitt, 1999; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Proffitt et al., 2003; Ramenzoni et al., 2008); however, the effect of additional weight on perceiving reaching and grasping capabilities is currently unknown.

When carrying weight, a person's centre of mass shifts according to the placement of the mass, affecting how they perceive and actualise affordances (Malek & Wagman, 2008; Ramenzoni et al., 2008; Regia-Corte & Wagman, 2008). Regia-Corte and Wagman (2008) asked participants to perceive how far up an inclined surface while not carrying weight, and when weight was attached to their back and above their head. To determine the participants' perceptual boundaries, they stood in front of an adjustable surface (starting at 15 or 40 degrees) and provided verbal instructions to increase or decrease the inclination. Participants perceived that the maximum incline that they could stand on was 30.1 degrees while not carrying any weight; 26.4 degrees while carrying weight (4.77 kg) on their back, and 24.7 degrees when carrying the weight above their head (authors did not provide perceptual accuracy scores). As the additional mass shifts the centre of mass upward, more muscular force is required to counteract the increased torque around the ankles, which may affect the amount of sway that is perceived as tolerable (Adolph & Avolio, 2000; Regia-Corte & Wagman, 2008). Moreover, the muscular force required to control sway (Bhalla & Proffitt, 1999; Proffitt et al., 1995), and this may affect the participant's perception and actualisation of their capabilities.

Climbing routes often take 2 to 7 minutes to ascend, where climbers spend approximately 62% moving (For review see, Watts, 2004). This indicates that climbers may experience acute fatigue induced by the climb. It has been shown that fatigue effects how a person perceived hill slant (Bhalla & Proffitt, 1999), and target distance (Proffitt, 2006); however, these studies manipulated fatigue in a binary fashion (exhausted or not) and failed to account for the accumulating effects of fatigue. Pijpers et al. (2007) examined the effect of accumulating fatigue on maximal overhead reach-and-grasp and found that both perceived and actual maximal reach-and-grasp decreased by 10cm and 2 cm respectively at high levels of fatigue (e.g. RPE 18-20), suggesting that a participant's perceived capabilities change in accordance with their actual capabilities. Perceived limits of reaching are affected by an ability to remain balanced (Carello et al., 1989; Robinovitch, 1998). Although reaching overhead offers minimal perturbation to balance (Fischer, 2000), reaching horizontally moves the centre of mass and requires postural adjustment to maintain balance. In this case, fatigue may affect the accuracy of perceiving maximal horizontal reach and grasp limits.

To date, a substantial amount of the reaching literature has examined how changing action capabilities (fatigue, additional mass) affect the perception of *overhead* reach. In climbing and other daily tasks, it is also common to reach horizontally. Therefore, the aim of the present study was to investigate how load, load position and fatigue affected perception of the maximal boundary of horizontal reach- and grasp-ness for climbers and non-climbers. We hypothesised that climbers would be more accurate under different constraints due to their experience in lateral reaching under conditions where their action capabilities are changed.

4.3 Methods

4.3.1 Participants

Based on previous research (Pezzulo, Barca, Bocconi, & Borghi, 2010; Seifert et al., 2018), a total of ten climbers (8 males, 2 females) and nine non-climbers (9 males), aged 16 to 45 years, volunteered to participate in the experiment. Given the inclusion criteria (expertise) it was difficult to get more participants within the Perth area. The climbers were rated from intermediate or above in terms of ability (i.e., +22 on the Ewbank climbing difficulty scale) with a minimum of 24 months climbing experience. The non-climbers had no prior climbing experience either competitively or recreationally. All participants were healthy and injury free at the time of testing. Prior to the study participants signed a written informed consent, with approval provided by the participating institution's Human Ethics Committee. For the testing they wore sport clothing with comfortable shoes, and a climbing harness.

4.3.2 Experimental setup

Participants attended four testing sessions, separated by a minimum of four days to allow the participants to recover from residual fatigue. Each session took approximately 90 minutes to complete. For this study, the maximal boundary of reach was defined as the maximal distance where the participant could lean against the side of the assessment hold for 3 s; maximal boundary of grasp was defined as the maximal distance where the participant could grip the assessment hold with their hand for 3 s. For both types of reach (touch, grasp), the participants were told to imagine reaching while balancing on one foot and that their subsequent movement would be to move the foot towards the middle of the wall, even though no hold was present (see Figure 7).

Figure 7. Possible hold sizes and body positions. From left to right, top to bottom (a) small hold, (b) single leg reach.

Similar to the work of Pijpers et al. (2007) the assessment holds, were attached to a horizontal sliding mechanism (that could move a distance of 97 cm) constructed using a ball screw and a stepper motor controlled by an Arduino (Interactive Design Institute, Ivrea, Italy). The sliding mechanism was placed 120 cm from the starting hand hold. A joystick allowed the experimenter to move the hold horizontally at a fixed speed of 2 cm/s. To hide any reference points, the sliding mechanism was mounted flush with the climbing wall and the wall was painted black. Furthermore, a black curtain was placed over the middle section of the wall, with a channel cut so the sliding mechanism was visible.

Participants estimated their maximal static horizontal reach and grasp while standing with both feet on two-foot holds (see Figure 8). The foot holds were attached to separate wooden panels, and the height of the panels was adjustable, such that the participant's acromion process could be placed in line with the middle of the horizontal sliding mechanism. The participant gave three perceptual estimates on each side of the wall (i.e. reaching to the left and reaching to the right) for three conditions: load position (shoulders and hips), mass of load (0% and 10% of body mass) and fatigue. The load and position trials were presented in a random order, with the maximal fatigue condition (10% hips or 0%) always occurring at the end of each session for logistical reasons. In each of the first two sessions, the participants completed 24 estimates for the baseline measures (3 estimates x 2 hands x 2 reach modes x 2 load conditions) and 12 estimates for the fatigue condition (3 estimates x 2 hands x 2 reach modes). In the final two sessions, the participants provided 12 estimates for *only* the fatigue condition (3 estimates x 2 hands x 2 reach modes). All trials were presented in a randomised order.

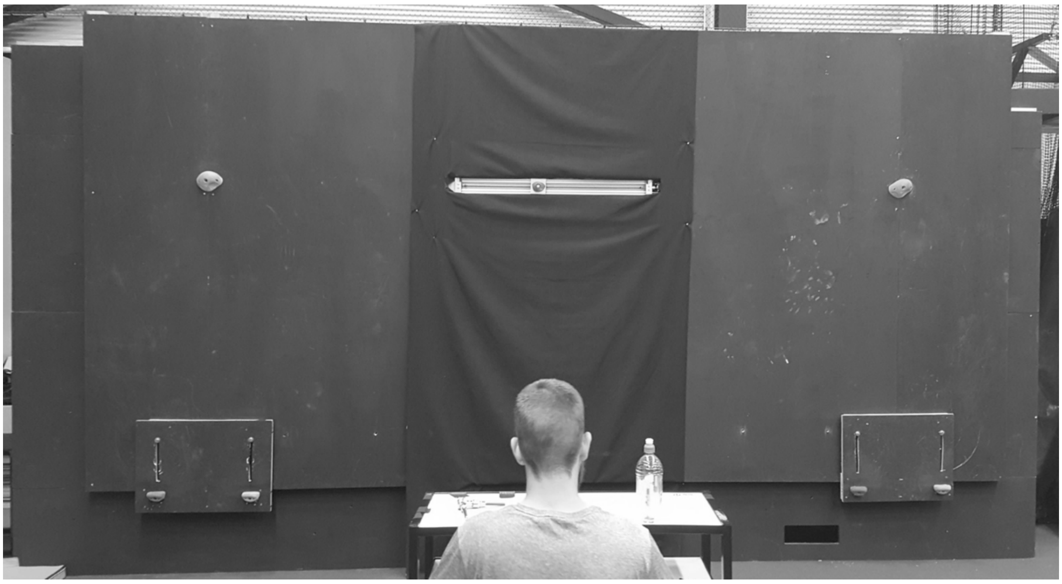
Figure 8. Experimental Setup with examiner (seated)

For the initial estimate the assessment hold was placed at the end of the sliding mechanism closest to the participant. For subsequent estimates, the assessment hold was randomly placed either side of their previous estimate at 10, 15, or 20 cm intervals. When the participant was satisfied with the assessment hold location, they instructed the investigator when to stop the sliding mechanism. The participants were allowed to make as many corrections until they were satisfied. When the participants signalled for the sliding mechanism to stop, they were prompted with "closer or further?" by the investigator until the participant stated they were happy and stepped off from the foot holds. The distance along the slide was measured using a tape measure out of sight of the participant (Walsh, 2019 Study 1).

For the load conditions, the participants were weighted with 10% body mass at the hips or shoulders, or with no weight. The participants wore a training vest (Armortech, Flex Fitness Equipment, Perth, Western Australia) for the shoulder condition, or a dive belt (Atlantis Scuba, Texas, USA) for the hips conditions. The mass of the load was measured to the closest 0.5 kg. For the maximal fatigue protocol, the participants completed 12 isometric hangs on a metal bar hanging from a 10-degree inclined climbing wall, with no additional weight or 10% of body mass added around their hips for each session. The participants completed two sessions for each of the weighted and unweighted conditions, which were randomised. The participants gripped the bar with their hands shoulder width apart in a pronated position and maintained 90-degree flexion at the elbows. Following the procedure by Mermier, Janot, Parker, and Swan (2000), the participants elbow flexion was visually inspected by the chief investigator, ensuring the upper arm and shoulder was perpendicular to the forearm. During each hang, the participants were given verbal encouragement, and corrections to technique (e.g. up, down). If the participant dropped too low they were instructed to pull up; if they were unable to pull up by the third instruction (e.g. up, up, up), the trial was terminated. Once the participant let go or was unable to pull themselves up, they immediately rated their overall perceived exertion (score from 6 to 20), and then stepped up onto the climbing wall to provide an assessment of their reach- or grasp-ness. Following the assessment of reach, they were given 3-minutes passive rest before the next isometric hang. RPE scores and hang times were recorded.

4.4 Procedure

Participants completed both baseline and fatigue trials during the first two testing sessions, and fatigue trials and actualisations in the final two testing sessions. During each testing session, participants wore a harness and stood in a standardised position on the portable climbing wall. For the standardised position, participants were required to have both feet on the foot holds at all times and to hold a fixed hold with their non-assessment hand, keeping their assessment hand by their side. Prior to getting on the wall, the participants were instructed the mode they were to perceive (e.g. single leg reach with the right hand). For the encumbrance conditions, the participants wore a weighted training vest or dive belt immediately before standing on the wall to provide their estimates. This procedure was repeated until all estimates were recorded. Once the participants were on the wall in the standardised position, the sliding hold was moved by the chief investigator using a joystick. Participants provided three perceptual estimates for reach- and grasp-ness for both hands for each condition at random, totalling 24 estimates for the first two sessions (3 estimates x 2 hands x 2 reach modes x 2 load conditions) and 12 estimates per session (3 estimates x 2 hands x 2 reach modes) for the 10% hip and 0% fatigue condition.

When the participant was satisfied with the placement of the assessment hold, they stepped down from the wall and walked behind a screen to ensure they could not see the wall. During this time, the investigator measured and recorded the distance of the assessment hold. Reach estimates were measured from the middle of the fixed hold to the near side of the assessment hold. As participants exert force through the objects centre of mass when grasping (Lukos, Ansuini, & Santello, 2007; Lukos, Ansuini, & Santello, 2008), grasp estimates were taken from the middle of the fixed hold to the middle of the assessment hold. The position of the assessment hold was then reset for the next trial, and the participant was instructed to re-enter the testing area. Each trial and the starting position of the assessment hold were presented in a random order.

At the end of the fourth session, once the participants had completed all of the perceptual estimates, their actual maximum reach and grasp assessments were recorded. The assessment hold was moved to the side of the mechanism where the participant either placed their fingers against the side of the hold (reach-ness) or grasped the hold (grasp-ness). When the participants were in the correct position, the assessment hold was moved until the participant started to fall off. From there the hold was brought closer until participant said "stop". They maintained contact with the hold for at least 3 s to ensure they could fulfil the reach- and grasp-ness criteria. After the 3 s, participants were asked closer or further until they were happy. If re-adjustments were made, the participants were required to maintain contract with the hold for 3 s. This was repeated for the load mass, load position, and fatigue conditions. The participants provided one actual maximal assessment for each condition.

4.5 Data Analysis

A π (Pi) number was calculated as the ratio of perceived and actual maximal horizontal reach- and grasp-ness (Pepping & Li, 2000). Values under 1 indicated an underestimation, values greater than 1 were an overestimation, and a value of 1 was perfect (Croft, Pepping, Button, & Chow, 2018). To determine if perceptual estimates are body scaled, a secondary Pi number (π_2) was calculated as the ratio between perceived horizontal reach- and grasp-ness and arm-span. All statistical analyses were conducted using the lme4 (Bates, Mächler, Bolker, & Walker, 2014) and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017) packages in the R statistics program (R Core Development Team, 2016).

To understand how fatigue, load and load position affected the perception of maximal reach and grasp between climbers and non-climbers, we constructed linear mixed effect models with binary predictors of experience and reach mode. We modelled the interaction between experience and reach modes (Model 1: $\pi \sim$ expertise * mode + (1|load) + (1|fatigue) + (1|ID)), where ID refers to each subject and additive effect of experience and reach modes (Model 2: $\pi \sim$ expertise + mode + (1|load) + (1|fatigue) + (1|ID)) on the maximal perception of action boundaries for fatigue, load, and load position using linear mixed models. The same procedures were followed to determine the effect of object size and support of support on body scaled estimates (Model 3: π_2 ~ expertise * mode + (1|load) + (1|fatigue) + (1|ID)), where ID refers to each subject and additive effect of experience and reach modes (Model 4: π_2 ~ expertise + mode + (1|load) + (1|fatigue) + (1|ID)). Coefficients for load, load location, and fatigue were to see how much variation they accounted for in the π values. Based on these results, non-contributing factors were removed from the final model. Significance was set at an alpha level of $p \leq 0.05$, with all models were checked for normality and robustness.

4.6 Results

Both climbers and non-climbers' perceptual accuracy was not significantly affected by additional load, load positioning, fatigue and expertise, whereas significant differences were found when changing between reach modes. Overall, both climbers and non-climbers provided more accurate estimates for their action-scaled reach-to-grasp affordances; however, reach-to-support was more accurate when examining their body-scaled affordances. On average, climbers and non-climbers reported similar RPE scores for unloaded (15.5 and 16.9 respectively) and loaded (15 and 17.1 respectively) conditions. Moreover, climbers mean hang time was longer than non-climbers for the unweighted hang (28.8s and 21.7s respectively) and weighted hang (24s and 17.3s respectively).

Perceptual judgement of action boundaries for reach and grasp

Non-climbers tended to underestimate their maximal reach (Table 5) and grasp (Table 6). In contrast, climbers appeared to overestimate their maximal boundary of reach (Table 5) and grasp (Table 6). Non-climbers tended to show consistent estimates in both load conditions (0.9 for left hand, 0.98 and 0.97 right hand for shoulders and hips respectively), with a similar trend demonstrated when perceiving grasp. In comparison, climbers showed consistent estimates between hands in both load conditions (1.03 for left and 1.0 for right), but estimates improved when perceiving grasp (from 1.04 to 1.03 for left hand and 1.02 to 1.00 for shoulders on right hand). In the fatigue condition non-climbers estimates increased except for the loaded left-hand hang condition. In comparison, climbers showed consistency between baseline and fatigued estimates

Table 5. Perceived-actual ratios for reach for each load and fatigue conditions for climbers and non-climbers (means ± sd).

	Climbers					Non-Climbers				
	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%
Left	1.00 ± 0.09	1.03 ± 0.06	1.03 ± 0.07	1.05 ± 0.07	1.04 ± 0.06	0.98 ± 0.05	0.99 ± 0.04	0.99 ± 0.04	1.00 ± 0.05	0.98 ± 0.04
Right	1.01 ± 0.08	1.00 ± 0.07	1.00 ± 0.07	1.01 ± 0.07	1.01 ± 0.07	0.95 ± 0.05	0.98 ± 0.04	0.97 ± 0.04	0.97 ± 0.05	0.96 ± 0.04

Table 6. Perceived-actual ratios for grasp for each load and fatigue conditions for climbers and non-climbers (means ± sd).

	Climbers					Non-Climbers				
	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%
Left	1.04 ± 0.07	1.03 ± 0.06	1.03 ± 0.07	1.04 ± 0.07	1.04 ± 0.07	0.97 ± 0.04	0.99 ± 0.04	0.99 ± 0.04	1.00 ± 0.04	0.99 ± 0.03
Right	1.02 ± 0.07	1.00 ± 0.07	1.02 ± 0.08	1.01 ± 0.06	1.03 ± 0.06	0.94 ± 0.04	0.98 ± 0.04	0.98 ± 0.04	0.98 ± 0.04	0.97 ± 0.04

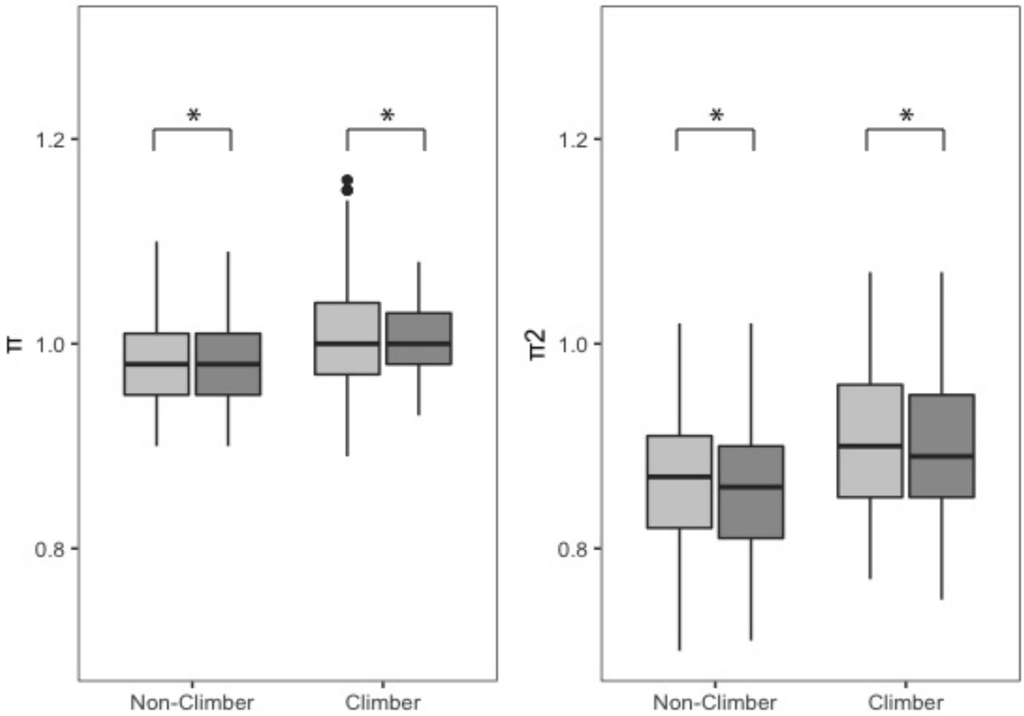

Figure 9. Perceived-actual ratios for climbers and non-climbers for action (π) and body (π2) scaled reach (light grey) and grasp (dark grey) boundaries respectively. Lines, boxes and vertical bars represent mean, interquartile range and range respectively.

Differences in climbing experience did not significantly affect perceptual accuracy ($F_{(1, 19)} = 4.19$, $p = 0.054$). When controlling for experience across climbers and non-climbers, reach mode did not show a significant effect ($F_{(1,2257)} = 3.46$, $p = 0.06$), on the participant's perceptual accuracy; however, for both expertise and reach action when controlling for expertise, significance was almost achieved. The coefficients for load, load location, and fatigue revealed that neither variables accounted for significant variation in reach/grasp accuracy. Moreover, changing reach mode significantly affected the participant's perceptual accuracy of their maximal horizontal capabilities ($F_{(1,2257)} = 9.74$, $p = < 0.001$).

Perceptual judgement of body scaled boundaries for reach and grasp

Both groups tended to underestimate their maximal reach (Table 7) and grasp (Table 8); however, climbers provided more accurate estimates for every condition.

Table 7. Body scaled ratios for reach for each load and fatigue conditions for climbers and non-climbers (means ± sd).

	Climbers					Non-Climbers				
	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%
Left	0.93 ± 0.09	0.92 ± 0.08	0.93 ± 0.08	0.94 ± 0.09	0.92 ± 0.08	0.87 ± 0.07	0.87 ± 0.07	0.88 ± 0.07	0.87 ± 0.07	0.86 ± 0.07
Right	0.93 ± 0.09	0.90 ± 0.08	0.91 ± 0.08	0.91 ± 0.09	0.91 ± 0.08	0.85 ± 0.07	0.86 ± 0.86	0.86 ± 0.07	0.86 ± 0.08	0.84 ± 0.07

Table 8. Body scaled ratios for grasp for each load and fatigue conditions for climbers and non-climbers (mean ± sd).

	Climbers					Non-Climbers				
	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%
Left	0.93 ± 0.09	0.92 ± 0.07	0.92 ± 0.08	0.94 ± 0.09	0.92 ± 0.08	0.86 ± 0.06	0.87 ± 0.06	0.87 ± 0.06	0.87 ± 0.06	0.86 ± 0.06
Right	0.92 ± 0.09	0.89 ± 0.08	0.90 ± 0.09	0.91 ± 0.09	0.90 ± 0.07	0.84 ± 0.06	0.85 ± 0.06	0.85 ± 0.06	0.85 ± 0.06	0.84 ± 0.06

Differences in task expertise did not significantly affect the participant's perceptual accuracy of their maximal horizontal capabilities ($F_{(1, 19)} = 3.30$, $p = 0.084$). When controlling for experience across climbers and non-climbers, reach mode did not show a significant effect ($F_{(1,2257)} = 1.31$, $p = 0.25$), on the participant's perceptual accuracy. Additionally, changing reach mode significantly affected the participant's perceptual accuracy of their maximal horizontal capabilities ($F_{(1,2257)} = 32.64$, $p = < 0.001$).

Individual differences in perceptual accuracy

Visual inspection of participants data revealed some variance, with participant 19 providing the greatest variance with action (0.97-1.24) and body scaled (0.87-1.18) boundaries. As expected, all participants actual reach and grasp boundaries decreased by 1 to 7 cm when encumbered and fatigued when compared to their baseline estimates. Of the 4 participants who underestimated their capabilities when fatigued, 3 (75%) also underestimated their capabilities when encumbered. In some cases, the participants actual boundaries of reach and grasp did not change (Table 9).

Effect of fatigue

Changing task expertise significantly affected the participant's perceptual accuracy of their maximal horizontal action capabilities ($F_{(1,2275)} = 70.67$, p = < 0.001). Additionally, differences in reach mode significantly affected the participant's perceptual accuracy of their maximal horizontal action capabilities ($F_{(1, 2273)} = 6.4$, $p = 0.014$). When controlling for experience across climbers and non-climbers, reach mode did not show a significant effect ($F_{(1,1437)} = 0.91$, $p = 0.33$), on the participant's perceptual accuracy. Analysis the RPE scores showed significant differences between the fatigue states ($F_{(13,886)} = 2.71$, p = < 0.001); however, no interaction effects were found when controlling for RPE and expertise ($F_{(12,885)} = 1.97$, $p = 0.90$).

Effect of encumbrance

During the maximal fatigue protocol, non-climbers reported higher ratings of perceived exertion in the non-additional load than the additional load condition (mean 17.09 and 16.92 respectively). In contrast, climbers reported higher ratings of perceived exertion in the additional load than the non-additional load condition (mean 15.56 and 14.98 respectively). For both climbers and non-climbers, hang times were higher in the non-additional load conditions (28.28 s and 21.73 s respectively) than the load condition (23.97 s and 17.3 s respectively).

Table 9. Actual reach and grasp for each load and fatigue conditions for climbers and non-climbers (means ± sd).

		Climbers					Non-climbers				
Mode	Hand	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%	0%	Shoulder 10%	Hips 10%	Hang 0%	Hang 10%
Reach	Left	1.66 ± 0.11	1.64 ± 0.11	1.66 ± 0.12	1.64 ± 0.10	1.63 ± 0.10	1.64 ± 0.09	1.62 ± 0.09	1.64 ± 0.09	1.61 ± 0.08	1.62 ± 0.10
	Right	1.68 ± 0.11	1.65 ± 0.12	1.67 ± 0.11	1.67 ± 0.11	1.65 ± 0.11	1.67 ± 0.07	1.63 ± 0.09	1.64 ± 0.09	1.63 ± 0.10	1.62 ± 0.09
Grasp	Left	1.65 ± 0.11	1.65 ± 0.11	1.65 ± 0.11	1.64 ± 0.11	1.63 ± 0.10	1.63 ± 0.09	1.62 ± 0.09	1.62 ± 0.09	1.61 ± 0.09	1.60 ± 0.10
	Right	1.65 ± 0.12	1.65 ± 0.12	1.65 ± 0.12	1.64 ± 0.13	1.61 ± 0.12	1.64 ± 0.08	1.60 ± 0.10	1.60 ± 0.10	1.61 ± 0.11	1.60 ± 0.10

4.7 Discussion

The present study investigated the influence of experience on the maximal perception of reach- and grasp-ness for different amounts of fatigue, load positions and load. The main finding of this study is that changing reach modes significantly affected the participants' accuracy of their perceived maximal action- and body-scaled boundaries. Additionally, changes to fatigue, load and load positions did not account for any significant variation in the model used to assess reach accuracy, suggesting these factors do not affect perception and interaction with a hold; however, the results suggest that the fatigue manipulation was effective. Our results support the hypothesis that reach mode, but not load position, affects perceptual accuracy of reach; however, these results could be explained by the participants' lack of need to move their centre of mass after contacting the target hold.

Perception of Action Boundaries

Our results showed that estimation errors differed for reach and grasp for both action- and body-scaled boundaries. These findings suggest that the manner in which a person interacts with an object can affect how they calibrate their maximal horizontal boundary of reach- and grasp-ness- specifically with participants scaling reach- and grasp-ness to their action capabilities. Previous literature has shown that people interact with objects differently depending on the goal of the task (Lukos et al., 2007; Lukos et al., 2008; Sartori et al., 2011) and calibrate reach distance to the object's functional feature (Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009). For example, Linkenauger et al. (2009) found that participants judged hammers to be farther away when handle orientation impeded grasp with their dominant hand, although target distance remained the same. Since non-climbers lack experience in performing maximal reach in order to move their body, this could have contributed to such findings. Moreover, the non-climbers' conservative body-scaled estimates could have been limited by their ability to balance on the climbing hold and reconfigure their centre of mass to prevent falling. Contrary to instructions, it could be possible that climbers perceived dynamically moving themselves towards the hold prior to reaching and grasping – extending how far they would be able to reach and grasp, as evidenced by the consistent classification of over-estimators when analysing action-scaled capabilities

Contrary to previous findings (Boschker & Barker, 2002; Hove et al., 2006), our results appear to suggest that task experience did not contribute to perceptual accuracy in the non-fatigued trials. A few reasons could be offered to explain this result. Firstly, it is possible the holds used were too similar in shape and size to highlight any perceptual differences between the groups. Secondly, the participants were not required to release the start hold and use the target hold for support. While the participants did grasp the hold during testing, it is possible that the participants did not grasp the hold in a manner whereby they could use that hold without readjusting their grip to make their next movement.

Furthermore, our results do not appear to support previous findings that fatigue effects perceptual accuracy. One possible explanation for this result is that climbing is a full body locomotor activity and fatiguing the arms does not affect the participant's ability to control their balance. As the participant's base of support is limited by their foot positioning, fatiguing the participant's arms would offer a minimal perturbance to balance. Moreover, as the participants did not release the first hold once they grasped the target hold, it is possible that fatigued affected their ability to support themselves with one hand.

However, task expertise was a contributing factor for participants in the fatigue condition when comparing under-, accurate- and over-estimators. One interpretation of this result is that, the non-climbers' conservative estimates could have been limited by their ability to balance on the climbing hold and reconfigure their centre of mass to prevent falling. In comparison, climbers were able to either accurately perceive (within 5 cm) or overestimate their maximal action capabilities boundary. The difference between accurate- and over-estimators could in part be explained by their climbing expertise. Climbers who over-estimate reported climbing grades mid to high 20s whereas accurate climbers reported climbing grades in the low to mid 20s. It is likely that the over-estimators have more experience completing technically challenging climbs where smaller holds and dynamic jumping movements are required.

Our results failed to show any significant findings for the load conditions. One possible explanation for this result is that load affects the participant's ability to move but not reach or grasp a hold. Research suggests that load affects how people perceive and realise action boundaries by increasing the muscular force to act and the permissible postural sway (Regia-Corte & Wagman, 2008); however, in this study the participants were not required to move their body after making contact with the hold. Future studies should examine the effect of load on the climber's maximal ability to reach and grasp a hold when a movement is required.

Our results on maximal reach-ness are comparable to Croft et al. (2018) who found that children underestimated maximal horizontal reach-ness. From a practical perspective, horizontal reach- and grasp-ness is important for climbers who are frequently required to make extreme reaches and grasps. Our results suggest that climbers should be more accurate at determining their maximal horizontal action-scaled boundary of reach (1.01 for climbers and 0.98 for non-climbers), grasp (1.02 for climbers and 0.97 for non-climbers) and their maximal horizontal body-scaled boundary of reach and grasp.

4.8 Limitations

The methodology used in this study was limited to the participants perceiving unsupported reach- and grasp-ness; however, during the actualisation protocol the participants started off and remained in contact (supported) with the assessment hold until their maximal boundary of reach- and grasp-ness. We acknowledge that this design may have limited the sensitivity or validity of the measurements. While some research has asked the participants to stop the assessment object and immediately reach for it (Pijpers et al, 2007), we believe that employing this methodology would have presented numerous challenges. From a pragmatic standpoint, rock-climbers often dynamically reach for a hold, using their opposing leg for a counterbalance when a hold is near their maximal action boundary – resulting in many repeated actualisations. If the participants were to continually reach and grasp for the hold, it is possible that the sliding mechanism would have been damaged or broken. Moreover, the participants would have been required to repeat the fatigue protocol for each attempt of determining their maximal action capabilities – which we believe would have affected the participants motivation to provide an accurate determination of their maximal capabilities.

4.9 Conclusion

In this study, we examined the influence of expertise on the maximal perception of reach- and grasp-ness for load, load position and fatigue. Overall, both climbers and non-climbers were reasonably accurate in perceiving their action- and body-scaled boundaries. Three important findings have emerged from this study. First, the manner in which the perceiver planned to interact with the hold significantly affected the perception of action- and body-scaled boundaries. Secondly, expertise level was a significant contributor to perceptual accuracy in the fatigue condition once the participants were classified into under-, accurate and over-estimators. Finally, load and fatigue did not significantly contribute to the perception of action and body scaled boundaries.

CHAPTER FIVE

The effect of fatigue on climbing fluidity and hand movement

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5.1 Abstract

In rock climbing, climbers use their arms to climb and regulate their posture on the wall, subjecting the localised musculature to fatigue. For climbers, fatigue is the primary cause of falls, but little is known about how fatigue affects climbing fluidity and a climber's hand movements. The present study examined the effect of fatigue on climbing fluidity and hand movements before and after a maximal upper body hang. Climbing fluidity was assessed by examining the hip jerk and global entropy index. Seventeen climbers completed three repetitions of a climbing route (21 on Ewbank scale) with different levels of localised arm fatigue; non-fatigue, maximal fatigue and recovery. Climbers' movements were tracked using 3D motion capture, and their hand movements assessed using notational analysis. Results showed no significant difference between hip jerk or global entropy index when fatigued although climbers fell more often when fatigued. Moreover, no significant differences were found between exploratory (27.5, 21.1, 23) and performatory (1.6, 1.5, 1.9) hand movements for non-fatigue, fatigue and recovery respectively. This study suggests that localised arm fatigue is sufficient to affect a climber's ability to stay on a climbing wall, but does not affect their fluidity.

Keywords: Rock Climbing, Movement, Hand Movement

5.2 Introduction

In all motor tasks, as we accumulate experience our movements tend to become smoother, and more precise (Seifert et al., 2018); however, as we experience neuromuscular fatigue our movements become less accurate (Forestier & Nougier, 1998). Neuromuscular fatigue is defined as the inability to maintain a given force output (Girard & Millet, 2009; Lepers, Theurel, Hausswirth, & Bernard, 2008). In rock climbing, as climbers accumulate experience they tend to move with greater agility and a less power-focused climbing style (Sibella, Frosio, Schena, & Borghese, 2007). Indeed, skilled climbers' fluid movements have been equated to an oscillating pendulum (Cordier, Dietrich, & Pailhous, 1996). However, climbing routes may take several minutes to ascend (Watts, 2004), and the time limit in lead-climbing competition is 6 to 8 minutes – suggesting that the climber may experience acute bouts of neuromuscular fatigue. Localised neuromuscular fatigue has shown to reduce a climber's perceived and maximal overhead reach-to-grasp (Pijpers, Oudejans, & Bakker, 2007), which in turn may increase exploratory and performatory hand movements when the climber is highly anxious (Pijpers, Oudejans, Bakker, & Beek, 2006). The purpose of this study was to examine how fatigue affects hand movements during climbing and general movement fluidity.

Rock climbing is a complex form of locomotion, combining upper and lower limb movements with perceptual-motor exploration (Button, Orth, Davids, & Seifert, 2016; Seifert, Cordier, Orth, Courtine, & Croft, 2017). For this reason, to understand how a climber is able to economically move through their environment, we must first explore a key factor that contributes to climbing fluidity; specifically the perception and realisation of reach and grasping affordances. In ecological psychology, a person's opportunities for action such as reaching for a climbing hold are either invited or not by the environment – a concept called "affordances" (Gibson, 1979; Turvey, 1992; Wagman, 2008). Perception of affordances is a continual personal process shaped by previous (Pijpers et al., 2007) and present experiences (Higuchi et al., 2011). Even if features of the environment afford the same action to two climbers, one climber may perceive the affordance and the other may not. Moreover, when a participant's action capabilities suddenly change (e.g. carrying additional load or being fatigued), they may require a period of physical and perceptual recalibration to explore changes to their altered capabilities and regain perceptual accuracy (Mark, 1987).

Proffitt and colleagues (Bhalla & Proffitt, 1999; Proffitt, Bhalla, Gossweiler, & Midgett, 1995) performed some of the earliest studies examining the link between fatigue and perceptual accuracy. They found that humans perceive environmental features like hill slant and distance as steeper or farther when fatigued (e.g. after a long run). Proffitt et al. (1995) induced central fatigue before the perceptual estimates, which was appropriate for their perceived task; however, in climbing the major cause of failure is peripheral fatigue in the hands and forearms (Watts, Daggett, Gallagher, & Wilkins, 2000). It is unknown whether peripheral fatigue similarly affects perceptual estimates of reaching during a climb. Pijpers et al. (2007) examined the influence of different levels of fatigue on maximal overhead reach-to-grasp. They found that both perceived and actual maximal reach-to-grasp only decreased at high levels of fatigue (e.g. rating of perceived exertion 18-20 on a 20-point scale), suggesting a functional fit between perceived and actual capabilities; however, the link between perceived and actualised reach-to-grasp and a climbing performance measure (e.g. movement fluidity or hand movements) was not explored.

Climbers use their hands to both climb and explore their environment (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008). Sibella et al. (2007) showed that skilled climbers touch fewer than three potential climbing holds prior to using a hold to move. In a series of studies, Pijpers et al. (2006) showed that climbers who experienced high anxiety had a reduced perceived and actual reach-to-grasp height (Study 1), and this reduction in reaching capabilities could have contributed to the significant increase in exploratory and performatory hand movements (Study 2). However, the authors acknowledge in the third study that it is unclear to what extent this result is due to a more conservative climbing style or attentional narrowing associated with anxiety. In a follow up study, Pijpers et al. (2007) showed that maximal fatigue (RPE 18-20) reduced the climber's perceived and actual overhead reach-to-grasp by 2 to 3 cm on average, but the link to hand movements was not explored.

Previous work in climbing has shown that climbers take on average 2 to 7 minutes to scale a 20 meter route or consisting of 27 moves (Watts, 2004). During this time, they often sustain isometric contractions in the forearms, which causes acute bouts of fatigue. Fatigue presents a considerable challenge to a climber's movement fluidity as it is the primary cause of falls (Watts, 2004). Various methods have been used to assess climbing fluidity: quantifying the path of climber's centre of mass curvature by using the global entropy index (Sibella et al., 2007), harmonic analysis of hip acceleration (Cordier et al., 1996) or assessing hip jerk (Seifert et al., 2014). While insightful, many of these methods are limited. Assessing the curvature of a climber's centre of mass only provides information on the spatial structure of a climber's fluidity and ignores stoppages. Whereas assessing a temporal fluidity metric such as harmonic analysis ignores hip displacement from the wall. Hip jerk is a valid indicator of movement fluidity (Seifert et al., 2014), as it assesses hip rotation and translation and can account for changes in hip displacement associated with different behaviours (e.g. postural regulation); however, it fails to account for the global path taken by the climber. Therefore, a comprehensive assessment of climbing fluidity may require combining two or more of the previously described methods.

To date, most of the current literature on climbing fluidity has focused on the role of experience. While there is a growing body of literature examining the influence of fatigue on reach-to-grasp (Pijpers et al., 2007) and grasping capabilities (Watts, 2004), the link to climbing fluidity is still unclear. Therefore, the aim of this study was to investigate the effect of fatigue on experienced climbers' movement fluidity and exploratory and performatory hand movements. It was hypothesised that fatigue would decrease climbing fluidity and increase the number of exploratory hand movements.

5.3 Methods

5.3.1 Participants

Based on previous research (Sibella et al, 2007), a total of seventeen climbers (16 males, 1 female) aged 20 to 40 years, volunteered to participate in the study. The climbers had above intermediate ability (i.e., +22 on the Ewbank climbing difficulty scale) with a minimum of 18 months continual climbing experience, climbing at least twice per week. All participants were healthy and injury free at the time of testing. Prior to the study participants signed a written informed consent, with approval provided by the participating institution's Human Ethics Committee. For the testing they wore sport clothing with climbing shoes, and a climbing harness.

5.3.2 Experimental setup

Participants attended one 90-minute testing session. Climbers were required to ascend a route three times as fluidly as possible while experiencing different levels of fatigue – no fatigue (control), maximally fatigued, and sub-maximal fatigue (after 2 minutes recovery). Movement fluidity was defined as a smooth continuous movement, minimising stops and jerky movements. The route was created by a professional route setter (see Figure 10), using yellow climbing holds across two 2 x 7 m walls and was graded as 22 on the Ewbank climbing difficulty scale. Participants traversed 4 meters across two walls (10° and 0° incline respectively), before climbing up the 7-meter wall. After each climb, climbers rated their overall fatigue on the Borg (1982) rating of perceived exertion (RPE). Climbers were asked to rate the route difficulty before the fatigue protocol and at the end of the testing session.

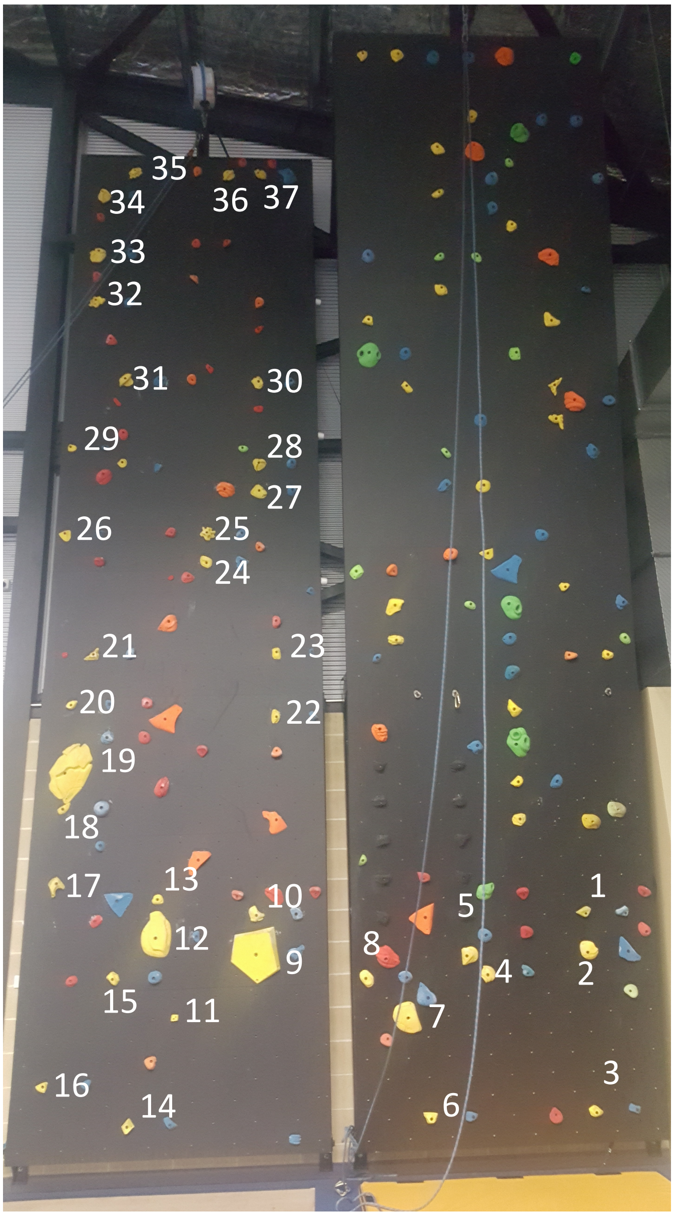

Figure 10. Location of 37 climbing holds for the climbing route

For the fatigue conditions, participants completed one isometric hang for as long as possible on jug holds on a hang board (see Figure 12), maintaining 90-degree elbow flexion. Following the procedure by Mermier, Janot, Parker, and Swan (2000), the participants' elbow flexion was visually inspected by the chief investigator to ensure that the upper arm was perpendicular to the forearm. During the hang, the participants were given verbal encouragement, and told to adjust their position up or down as necessary. If the participant dropped too low they were instructed to pull up; if they were unable to pull up by the third instruction (e.g. up, up, up), the trial was terminated, and hang time was recorded. Once the participant let go or was unable to pull themselves up, they immediately started climbing. No fatigue manipulation check was completed after the participant completed the hang.

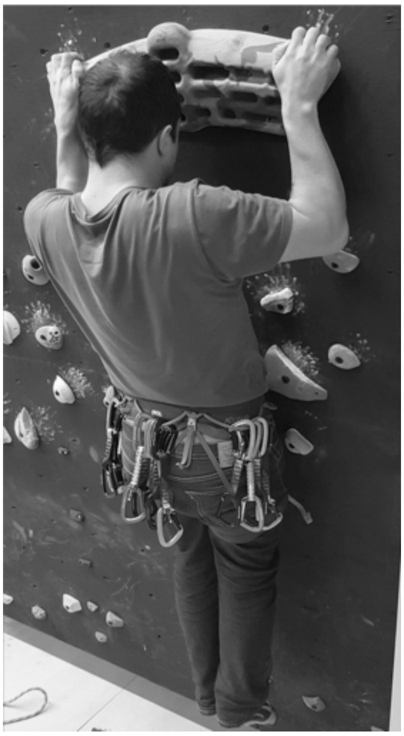

Figure 11. Maximal fatigue protocol where participants maintained 90-degree elbow flexion on a hang board

5.4 Data Collection

All climbing movements were recorded using a VICON Motion Capture System (Oxford Metrics Ltd., Oxford, UK), with 21 infrared cameras sampling at 100 Hz, capturing the locations of 70 retro-reflective markers. A total of 15 rigid body segments were created (head, thorax, pelvis, and left and right upper arms, forearms, thighs, shanks, hands and feet). Markers were attached to the anterior, medial, and posterior aspects of the skull, C7, T10, xiphoid process, sternum, anterior superior iliac spine, posterior superior iliac spine, iliac crest, acromion processes, medial and lateral epicondyles of humerus, lateral malleoli, and the posterior aspects of the calcaneus. A cluster of two tracking markers was placed on forearm, with three tracking markers placed on the posterior compartment of the upper arm, and anterior compartments of the thigh, and shank. An additional eight calibration markers were attached bilaterally on the lateral and medial aspects of the malleoli, and epicondyles of the femur - which were used to determine foot width and joint centre's respectively and were removed prior to climbing commencement. Markers were fixed to the skin with adhesive tape and were further supported by medical tape. The anterior superior iliac spine and posterior superior iliac spine markers were fixed to the harness over the anatomical landmarks. A volume of 4.00 x 7.00 x 2.00 m (X horizontal, Y vertical, and Z away from the wall, respectively) was calibrated using a wand as an experimenter was lowered by belay. A GoPro camera (Hero 5, San Mateo, California, USA) was placed 5 meters behind the climber facing the wall to record the climbers' movements.

5.5 Data Analysis

To ensure that no area outside of the intended route (e.g. area above holds 1 to 8 on the right wall) was incorporated into the climbing fluidity measures, the climb was divided into seven parts: four traverse segments and three vertical segments. The segments were defined as follows: section 1 – holds 1 to 17; section 2 – holds 18 to 21; section 3 – holds 21 to 27; section 4 – holds 27 to 30; section 5 – holds 30 to 32; section 6 – holds 32 to 34; section 7 – holds 34 to 37 (see Figure 10).

The three-dimensional positions of the reflective markers were reconstructed using VICON Nexus software (Oxford Metrics Ltd., Oxford, UK). All data were filtered using a 6-Hz low-pass Butterworth filter, with the cut-off frequency determined from residual analysis (Yu, Gabriel, Noble, & An, 1999). The coordinates were imported into Visual 3D software (C-Motion, Inc., Germantown, MD, USA) to create a full-body model to calculate the centre of mass for each participant. Segmental coordinate systems (shank, thigh, forearm, upper-arm, head, and trunk) were created in accordance to Wu et al., (2005). Full-body and segmental centre of mass were calculated for each participant for each trial.

Climbing Fluidity

Two measures of climbing fluidity were used; hip jerk and global index of entropy (GIE). Hip jerk was calculated by examining the rate of change of acceleration of the climber's centre of mass. Hip jerk (J_x^{GF}) was defined as:

$$J_x^{GF}(T) = C\int \frac{T}{0} \parallel x_x^{GF} \parallel^2 ds \, ,$$

where C was a normalisation constant to make the quantity dimensionless (Hogan, N & Sternad, D., 2009). Moreover, analysis of the variance of hip movement (amplitude) was calculated by quantifying the oscillation of the climber's centre of mass between each trail. Global index of entropy measures the amount of chaos versus order in a system and was calculated for the X, Y, and Z directions. The global entropy (H) was calculated by taking the logarithm of twice the length covered by the body centre of mass (LP) divided by the perimeter of the convex hull around the path (c). Global index of entropy (H) was defined as:

$$H = \ln \frac{2 * LP}{c} \, ,$$

where LP = CM path length, c = perimeter of the convex hull around LP. Jerk coefficient and global entropy index were calculated for each section of the climb for each climber. All statistical analyses were conducted using the lme4 (Bates, Mächler, Bolker, & Walker, 2014) and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017) packages in the R statistics program (R Core Development Team, 2016).

To understand how climbing fluidity was affected by the different levels of fatigue, we constructed linear mixed effect models using predictors of trial (no fatigue, maximal fatigue and sub-maximal fatigue respectively) and route sections. Jerk was modelled by examining the interaction between trial and section (Model 1: jerk ~ trial * section + (1|ID)). In a subsequent model, amplitude (Model 2: amplitude ~ trial * section + (1|ID)) was examined using linear mixed model. Global index of entropy was modelled for each section (Model 3: GIExy ~ section * trial + (1|ID); Model 4: GIEyz ~ section * trial + (1|ID); Model 5: GIEzx ~ section * trial + (1|ID)). Statistical significance was set at an alpha level of $p \leq 0.05$.

Hand Movements

To classify the participant's hand movements, GoPro footage for ten participants[1] were analysed frame-by-frame. For each trial, hand movements were classified as exploratory

[1] Some video footage was corrupt, and complete video data was only available for 10 participants

and performatory in accordance to Pijpers et al. (2006). We added a sub category to exploratory hand movements called regrip, where the subject released and re-grasped the hold without using it for support. To determine reliability, video data was analysed by two different assessors. The first reviewer had numerous years of climbing experience, whereas the second review had no climbing experience. There was a 100% agreement between observers for performatory, exploratory and regrip hand movements. All hand movements were analysed using a Chi-squared test with significance was set at an alpha level of $p \leq 0.05$.

5.6 Results

No main effect was found in terms of fatigue for hip jerk ($F_{(1,28189078)} = 0.77$, $p = 0.38$). Similar results were found between fatigue conditions for global index of entropy; GIExy ($F_{(1,324)} = 0.002$, $p = 0.96$), GIEyz ($F_{(1,312)} = 0.008$, $p = 0.93$), GIEzx ($F_{(1,323)} = 0.00$, $p = 0.99$). A significant difference was found for hip jerk amplitude and route section ($F_{(1,384)} = 5.31$, $p = < 0.02$). A comparison between hip jerk amplitude and route sections showed significant difference in amplitude between sections 1 and 2 ($F_{(1,80)} = 11.04$, $p = < 0.001$) with higher amplitude scores in the first section (2.87) than the second section (2.00). Falls were analysed in a post-hoc test to determine the effect of fatigue on climbing success. Fatigue resulted in more falls 23% (4/17) falls versus no falls when unfatigued. Climbers who fell in the fatigue trials also fell in the recovery trials, suggesting that 2 minutes was not enough time to sufficiently recover. Moreover, 75% of fall trials participants were in a 3-point of contact position and were moving. Interestingly, 62% (5/9) falls happened between holds 20 to 22, which requires the climber to change body position from the left to the right side of the wall.

Table 10. Number of performatory, exploratory and regrip hand movements and falls across the three fatigue conditions (means ± sd)

	Performatory	Exploratory	Regrip	Falls
Non-Fatigue	27.5 ± 2.12	1.6 ± 1.58	3.4 ± 3.1	0
Fatigue	21.1 ± 8.81	1.5 ± 1.78	3.3 ± 1.64	6
Recovery	23 ± 6.5	1.9 ± 3.03	3.8 ± 3.58	6

A chi-squared test did not show a difference in hand movements due to fatigue ($p = 0.60$)

Hand Movements

A chi-squared test did not show a difference in hand movements due to fatigue ($p = 0.60$). Performatory hand movements decreased from 27.5 to 21.1 and 23 for non-fatigued, fatigued and recovery respectively. Exploratory and regrip hand movements decreased from non-fatigue to fatigue but increased when comparing non-fatigue to recovery (see Table 1). Analysis of rating of route difficulty revealed that climbers perceived the route to be 20 on the Ewbank Scale. Moreover, 53% of climbers (9/17) ratings of route difficulty did not change before and after the fatigue protocol, whereas 29% of climbers (5/17) increased their ratings of route difficulty. Of the climbers who fell, 50% of climbers (2/4) did not change their rating of route difficulty, whereas 50% of climbers (2/4) increased their ratings of route difficulty.

5.7 Discussion

The present study investigated the influence of fatigue on temporal and spatial measures of fluidity and hand movements in experienced climbers. The lack of difference due to localised fatigue in their arms suggests that experienced climbers maintain the same climbing style as when unfatigued. Moreover, no significant difference was found between the type of hand movements (i.e. performatory and exploratory) when climbers were unfatigued, fatigued, or partly recovered. Such findings do not support our hypothesis that fatigue might affect climbing fluidity and the number of exploratory hand movements.

Previous research has shown that hip jerk reduces as a climber becomes familiar with a route (Seifert et al., 2014), and that fatigue contributes to a decrease in movement fluidity (Cortes, Onate, & Morrison, 2014). Perhaps surprisingly, our results do not support these findings although the climbers experienced maximal fatigue and climbed the same route three times. It is possible that the holds used may not have required considerable contribution from the forearms (Amca, Vigouroux, Aritan, & Berton, 2012). As the legs are used to support body mass (Quaine, Martin, & Blanchi, 1997), climbers may have compensated for arm fatigue by using their legs more. The route may not have been sufficiently difficult as the climbers judged the route to be a 19 on the Ewbank scale, which was well within their capabilities. It is possible that the climbers were not sufficiently fatigued to elicit any changes, but this seems unlikely since 23% of climbers fell at least once whence fatigued. Moreover, the route was primarily comprised of pinch and open grip holds, which do not require much contribution from the forearms when compared to crimp and 2 finger grips (Watts et al., 2008). It is also possible that the arms have a minimal contribution to climbing fluidity, as they control posture and position whereas the legs support the body mass (Quaine et al., 1997), thus inducing fatigue in the legs may have a greater effect on climbing fluidity.

The results also suggest that a climber's hand movements were not affected by different levels of fatigue. It could be interpreted that the climbers were familiar with the route after the first ascent and that local forearm fatigue was not adequate to elicit exploratory behaviours. Examination of the ratio of performatory to exploratory hand movements suggests the climbers seldom engaged in exploratory movements. While Pijpers et al. (2006) found that exploratory hand movements increase in high-anxiety conditions, it appears that fatigue does not induce similar action changes; however, it is possible that the climbing holds were placed too close together that when the climber was fatigued the average inter-hold distance still fell well within their altered action capabilities. Additionally, climbers did not have to use all of the yellow holds in the climb, therefore, it is likely that the route invited shorter reaches (hold 25 to 27) instead of longer reaches (26 to 27). Moreover, it is possible that maximal localised fatigue affects a climber's ability to remain in contact with a hold (Watts, 2004) and does not cause attentional narrowing that affects the realisation of affordances (Pijpers et al., 2006).

Currently most of the climbing literature (Seifert et al., 2004; Sibella et al., 2007) is focused upon describing climbing behaviours through measures of spatial (and occasionally temporal) fluidity. While these studies have provided valuable insight into how climbers move, not much attention has focused on how these measures change when fatigued. Our results suggest that despite the fatigue experienced by the climbers, they were able to maintain the same climbing style; however, climbers only experienced localised muscular fatigue to the forearms. From a practical perspective, climbing requires contribution from both the arms and legs to move, therefore future studies should examine the effect of whole-body fatigue on climbing fluidity. Of the climbers who fell, the notational analysis revealed that falls were typically experienced around holds 20 to 22 when attempting to move from the left side to the right side of the wall. Moreover, when climbers fell, 75% of them were in a 3 point of contact suggesting climbers may have had issues regulating posture during movement. Climbers appeared to engage in some exploratory behaviour (visual and motor) in the moments leading up to the fall, however, we were unable to quantify these behaviours and further analysis will be needed.

5.8 Limitations

While the study examined the effect of fatigue states on climbing performance, there are some limitations which may affected the results. Firstly, no objective fatigue manipulation check was used in the study. While there are ways to objectively measure fatigue (e.g. hand grip dynamometry, EMG) we believe that the time taken to complete these measures would have affected the results. As all of the participants were very experienced rock-climbers, they would have experienced physiological adaptations that aid recovery. Moreover, the fatigue conditions were presented in a fixed-order to replicate partner climbing, where it is common for a climber to experience maximal (or near maximal) fatigue and only have a few minutes to recover while their partner climbs.

5.9 Conclusion

In this study, we examined the influence of different fatigue conditions on climbing fluidity and hand movements. Overall, climbers were able to maintain climbing fluidity whether unfatigued, fatigued or partly recovered. One important finding from this study was that localised forearm fatigue induced by hanging was not sufficient to change experienced climbers' movement fluidity and their exploratory behaviours.

CHAPTER SIX

Conclusion

The present thesis describes three studies that sought to expand current knowledge surrounding reaching and grasping affordances. The purpose of this chapter is to summarise the findings of the three studies and discuss the theoretical and practical implications for future research in rock climbing and reaching. To achieve this, I will break down and review the findings from each chapter and then discuss the specific perception of affordances for reaching.

6.1 The Current Thesis

Chapter 3 investigated whether the perception of maximal static horizontal reach- and grasp-ness were affected by hold size (big and small) and body position (dual and single leg stance) in both climbers and non-climbers. Both climbers and non-climbers perceived reach- and grasp-ness on a climbing wall using an automatic sliding mechanism. Evidence showed that changing between reach- and grasp-ness significantly affected the accuracy of perceived maximal boundaries; however, task experience did not. An interaction effect between expertise and reach mode affected perceptual accuracy, but hold size and body position did not account for any variation. Together, these results suggest that how the participants planned on interacting with the climbing hold (reach or grasp) affected how they calibrated their maximal action capabilities and that experience in climbing was not necessary to be able to calibrate perception of affordances for reaching.

Given that climbing experience was not required to calibrate reaching accurately, we were interested whether circumstances that are only experienced by climbers (e.g. carrying additional mass) affected their ability to recalibrate. In Chapter 4 we investigated the effect of load (0 or 10% of body mass), load location (hips or shoulders) and fatigue (no fatigue and maximal fatigue) had on single leg perceived maximal horizontal boundary of reach- and grasp-ness. Using the same methodological approach as Chapter 3, both climbers and non-climbers provided estimates of their maximal horizontal boundary of static reach- and grasp-ness. The results of Chapter 4 echo those of Chapter 3, finding that reach mode significantly affected the participants' accuracy of their perceived maximal action boundaries, but expertise did not. Additionally, neither fatigue, load, nor load position accounted for any differences in reach accuracy. However, expertise was a contributing factor in the fatigue condition when participants were classified into under-, accurate- and over-estimators.

Finally, in Chapter 5 we examined movement fluidity and hand movements of experienced climbers when unfatigued, maximally fatigued and partially recovered. The data revealed that hip jerk and global entropy index were not affected by fatigue, but there were differences in different sections of the climb: the amplitude of hip jerk was higher in the first section (2.87) of the climb than the second section (2.00). The number of exploratory hand movements was not affected by fatigue. Taken together these results indicate that experienced climbers maintained a similar movement pattern irrespective of fatigue. These results in part may reflect the climbers' technical approach to climbing, where they use their arms and legs to regulate posture and produce force respectively (Quaine, Martin, & Blanchi, 1997).

6.2 Reaching to Touch versus Reaching to Grasp

The current thesis highlighted the importance of the goal of the reaching action. Climbers reach and grasp to achieve different goals: maintaining postural stability (Bourdin, Teasdale, & Nougier, 1998), exploring features of a hold (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008) and repositioning their body. Sartori, Straulino, and Castiello (2011) showed that participants' finger placement differed when the end goals changed (picking up or moving a water bottle). It is likely that in climbing, simply changing the goal of the reach requires the participant to reorganise both their finger and body to deal with the postural demands. The findings in Chapters 3 and 4 appear to support this conclusion as when participants changed between perceiving reach- and grasp-ness, the manner in which individuals interacted with the hold changed, which may have affected their perceptual accuracy (Wagner et al, 2018).

6.3 Task Expertise in Climbing

The results from Chapters 3 and 4 suggest that both climbers and non-climbers are accurate at perceiving the maximal boundary of reach- and grasp-ness, despite their differences in task experience. This is contrary to previous literature where task experience contributed to accuracy of perceived capabilities (Hove, Riley, & Shockley, 2006; Weast, Shockley, & Riley, 2011). One difference between those studies and the current study was in the type of task: their participants perceived specialised skills whereas ours perceived reach- and grasp-ness – actions that are performed countless times a day and are fundamental to daily living (Choi & Mark, 2004). People probably have more experience judging vertical reach than maximal horizontal reach, but we didn't find any differences when comparing our results to existing literature. Previous studies have found differences in perceptual judgement in different directions (Croft, Pepping, Button, & Chow, 2018), but those participants were children between 6 and 11 years old.

It is possible that differences in task experience would better manifest if the participants maximal boundary was judged on whether they could successfully execute the subsequent movement. Given that climbers use *both* their hands and feet to move, it is important that each movement facilitates the next movement. Therefore, in future studies, researchers should examine whether differences exist in maximal action boundaries when participants are required to successfully execute the movement following the reach or grasp. Moreover, climbers who consistently over- or under-estimate their reach or grasp capabilities could be explained by factors like risk-taking profiles or self-confidence as climbers who score high in self-confidence or risk-taking behaviour may engage in larger and more dynamic moves; therefore, future studies should examine the role of personality-based variables on reach and grasp perception

6.4 Environmental-Based Influences

The results from Chapters 3 and 4 suggest that both climbers and non-climbers are accurate at perceiving the maximal boundary of reach- and grasp-ness, despite the changes to hold size. This is contrary to previous research that has demonstrated changes to object size effect how the participant interacts with it (Baud-Bovy & Soechting, 2001; Lederman & Wing, 2003; Sartori et al., 2011). One difference between those studies and the current study was the goal of the task. In Chapters 3 and 4, the participants needed to use the hold to assist with the balance, whereas in the previous studies the participants were required to pick up the desired object. It is likely that the participants in Chapters 3 and 4 needed minimal area to lean against (reach-to-touch) or grasp (reach-to-grasp) in order to fulfil the testing protocol. In contrast, when people pick up an object, they must grasp the object in a manner that allows them to overcome the weight and fulfil any secondary objectives (e.g. move it or drink from it).

6.5 Organismic-Based Influences

Despite the changes to the participants base of support, encumbrance and fatigue states, they were able to accurate perceive their maximal boundary of reach- and grasp-ness. These findings of Chapters 3 and 4 are contradictory to previous research (Pijpers, 2007; Carello et al., 1989; Malek and Wagman, 2008). It is possible that methodological differences between our studies and previous research contributed to this. In Chapters 3 and 4, it is likely that the participants used their non-reaching hand on the starting hold to maintain support and correct any postural instability created from performing a maximal reach under each condition. Moreover, in Pijpers (2007) fatigue study, participants performed an over-head reach, requiring them to support their body weight with one hand, whereas in our studies the participants were able to use *both* hands to support their body weight.

6.6 Reaching for Locomotion

So how does the perception of action boundaries translate to movement? The results of Chapters 3 and 4 suggest that differences between experienced and inexperienced climbers are not due to inadequacies in perceiving maximal reach. Unlike many other tasks, ice and rock climbing are naturally constraining activities and so chaining movements together is crucial for success (Pezzulo, Barca, Bocconi, & Borghi, 2010). In climbing, knowing whether a hold can be grasped is important, but it is equally important knowing whether that support can be used to facilitate a subsequent movement. Climbers often preview a route to determine the most efficient way to climb. Future research should investigate the effect of route preview on climbing performance measures (e.g. climbing time, falls and performatory vs exploratory limb movements).

6.7 Climbing Fluidity

One explanation for the climbers maintaining climbing fluidity is that they climbed a route below their maximal climbing capacity and the route was comprised of crimps and open grip holds. Moreover, it is possible that experienced climbers were able to account for the effects of localised fatigue in their arms. How the climbers were able to do this remains unclear, however, we believe that the climbers adapted their climbing style. Given that localised fatigue was induced in their arms, it is likely that climbers relied on their legs more for support. This explanation supports the notion that in rock and ladder climbing the arms control posture and position whereas the legs support body mass (McIntyre & Bates, 1981; Quaine et al., 1997). It is possible that fatiguing the arms only affects the climber's ability to grasp a hold, with insufficient strength resulting in a fall and end of the climb. As the legs offer support to the climber, fatigue may affect the climber's force production capabilities and climbing fluency.

6.8 Implications for Reaching Research

It appears that inexperienced participants are equally capable as their experienced counterparts when determining maximal reach- and grasp-ness for objects with ambiguous features. This result suggests that inexperienced perceivers are able to draw on experience from similar tasks to assist with perceptual estimates. This appears to support the notion by Cole, Chan, Vereijken, and Adolph (2013) that accurate affordance judgement is affected by, but not limited to, skill in a particular action. Given that static reach-to-grasp actions are performed countless times a day (Choi & Mark, 2004), it seems highly plausible that inexperienced participants in this project were able to draw on previous experience where they grasp similar non-handled objects (e.g. fruits) to form a basis for their perceptual estimates. Future research is therefore encouraged to establish whether participants are able to transfer experience from similar tasks to maintain perceptual accuracy.

6.9 Limitations and future considerations

While this thesis has provided some valuable insight into how people perceive maximal reach and grasp affordances in naturally constraining environments, there are a few limitations. Firstly, in Chapters 3 and 4 the participants perceived unsupported reach- and grasp-ness; however, the participants remained in contact with the assessment hold when determining their maximal capabilities. Moreover, the participants were not required to perform a secondary movement (e.g. move foot towards the sliding mechanism). Producing the subsequent foot movement could have affected their maximal reach as they would have had to stay balanced on the hold when moving their body, instead of using the hold to lean against. Finally, in Chapters 4 and 5 the fatiguing protocol created localised fatigue in the arms; however, climbing requires the coordinated use of *both* the arms and legs to move. This could have affected the results as the participants may have used their legs more for support and locomotion, thus reducing the effect of fatigue on reaching capabilities and movement.

Many populations suffer from perceptual inaccuracies such as the elderly, stroke patients and individuals with heart disease, which can lead to falls. Thirty percent of adults over the age of 65 experience a fall (Australian and New Zealand Falls Prevention Society), with many falls experienced when older adults perform a secondary dual task (e.g. reaching while walking) (Rinaldi, van Emmerik, & Moraes, 2017). Impaired gait and balance have been identified as a risk factor for the elderly (Sherrington et al., 2011). It has suggested that exercise programs incorporating high challenge balance training and moderate to high progressive resistance training for a minimum of 2 hours per week for 25 weeks are beneficial (Sherrington et al., 2011; Tiedemann et al., 2011). As climbing requires perceptual-motor, perceptual-cognitive and dynamic balance - all factors that affect such populations - rock climbing could provide a novel program that could assist with balance, perceptual-cognitive and perceptual-motor functioning. Moreover, rock-climbing routes can become progressively more difficult by using different type and size holds.

In many daily life and sporting scenarios, people will often change between reaching for and grasping an object, changing how they calibrate their action boundaries. While people are able to accurately perceive their maximal boundary of reach- and grasp-ness, significant differences between the reach modes exist (Studies 1 and 2). This result has potential implications for future research – specifically task switching paradigms (e.g. switching from reach-to-touch to reach-to-grasp). Given that many objects present numerous grasping affordances, future studies should examine the effect of task switching has on calibrating reaching and grasping affordances.

6.10 Conclusion

This thesis was able to partially fulfil some of the primary aims laid out in the introduction regarding the factors that affect maximal perception of action boundaries and movement. Firstly, the thesis sought to investigate if the experience gained from sub-maximal horizontal reaching transferred to maximal horizontal reaching in rock climbing. Contrary to our hypothesis, experience gained from sub-maximal reaching did translate into the perception of maximal reaching and grasping affordances. It is possible that the holds used were very similar to many everyday objects and that more challenging climbing holds (e.g. crimps/micro crimps or slopers) may produce a different result. Secondly, the perception of maximal horizontal reach- and grasp-ness was not affected by hold size, body positioning, additional load or fatigue. This suggests that that both climbers and non-climbers were able to accurately calibrate even though some of the conditions may have been slightly unnatural to the non-climbers. Finally, in study 3 localised forearm fatigue was not sufficient to affect a climber's movement economy. It is likely that when rock climbing, climbers rely on using the arms and legs in sequence to support themselves and move up a route, therefore inducing localised fatigue in the arms or legs may not be sufficient to affect their movement economy.

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Appendix A- Information letter Study 1

Information Letter to Participants

Thank you very much for indicating your interest in participating in this study. The purpose of this document is to explain the study that you are going to participate. Please read carefully and understand the information below, and do not hesitate to ask any questions.

Project Title

Analysis of perceptual-motor calibration processes in indoor climbing

Researchers

This research project is being undertaken as part of the requirements of a Doctor of Philosophy (PhD, Sports Science) at Edith Cowan University (ECU).

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Further details on supervisors and School of Exercise and Health Sciences are available at http://www.sebhs.ecu.edu.au.

Purpose of the study

We are interested in determining the influence of body positioning, the shape of target hold on perception of reachability and graspability in the horizontal plane.

Eligibility

You will be eligible for this study if your age is between 16 and 45 yrs, have no history of major injury, have no significant vision problems, have no conditions that impede your ability to maintain balance and are injury free at the time of your participation in the study. You will be screened with a generic medical questionnaire consisting of several questions about your health and physical conditions. Once you are found to be eligible for the study, you will be invited to participate as a subject in this study.

Requirements

You will be required to complete 3 sessions (1 familiarisation session, 2 testing sessions). All testing sessions will comprise of a 5 min bouldering warm up session followed by approximately 40 min testing session, where will you be required to give your perception of your maximal boundary from your starting position (foot holds 50cm off the ground). Maximal boundary of reach will be defined as the furthest point where you can touch the object while maintaining balance. Maximal boundary of grasp will be defined by the furthest point where you can maintain hold of the object and still support your body mass. You will be required to determine your perceived reach and grasp while supporting yourself on a climbing wall. You will assume two (2) body positions, dual-leg and single-leg support (for description see below) and give 3 verbal estimates for horizontal (left and right) reach and grasp. You will be required to provide three estimates for each of the two (2) reaching modes, pinch to jug, and pinch-to-pinch, for each body position and reaching mode direction. The mechanism will slide according to your verbal commands until you believe you can no longer maintain a grasp/reach on the hold. The final testing session, your actual boundary of reach and grasp will be obtained. You will be required to wear all rock-climbing safety gear (harness, and shoes) for all testing sessions. You will be requested not to perform any strenuous exercise 2 days prior to the testing session and refrain from consuming caffeine and alcohol at least 12 hours prior to testing. Furthermore, all sessions will be recorded to ensure consistency in testing procedures and data collection.

Familiarisation session

During familiarisation session you will be acquainted with all testing procedures, and where you will be positioned. To familiarise yourself with the sliding mechanism, a demonstration will be given on how it works, as well as the verbal instructions you will need to give.

Exercise

You (as the subject) will be required to face a wall (foot holds 50 centimetres off the ground) and assess whether you believe you can maintain grasp/reach on a hold that is secured to a sliding mechanism. At the instant you believe you cannot maintain grasp on the hold, say stop and the testing session will conclude. For the study, you will be engaging in very minimal climbing. Each session will take approximately 50 to 60 minutes, including warm-up.

Equipment you will need

For this study you will need to bring your harness, rock climbing apparel, and normal sporting shoes.

Measurements

During the testing, we will be taking measurements of the distance of where you believe you can no longer maintain grasp of the hold, and where you believe you can no longer maintain balance on the hold.

Testing Procedures

Perception of grasp/reach – You will be required to give your perception of grasp/reach when positioned against a wall. Your perception of reach and grasp will be determined by verbally instructing the lead investigator to move a sliding pole (see picture below).

Body Positions – Throughout the testing you will be required to assume two positions, trimodal and bimodal. Trimodal means you will have two foot holds to place your feet on and one hand hold to support yourself. Bimodal represents one hand hold and one foot hold. For both conditions, you will need to support yourself, and feet must maintain contact with the supporting footholds.

Single-leg Dual-leg

Hand Holds – There will be two hand hold conditions, Pinch to Jug and Pinch to Pinch. For both conditions, the target hold will be a hold, with the target hold changing between Jugs and Pinch Grips.


Risks

The risks associated with this study are minimal. These risks may include a sore neck from looking up, falling and muscle strain; however, the possibility for these risk are very low. The reduce muscle strain, a 5 minute warm up will be implemented, and you will be required to stretch before any exercise.

Benefits

You will gain insight into the research process and techniques, and will also gain information about your perception of the horizontal environment. The results of this study will also be provided to you upon request.

Confidentiality of Information

All information provided by you will be treated with full confidentiality. Your contact information will only be accessible by the chief investigator during the period of the study. The information and data gathered from you during the study will be used to answer the research question of this study. People who will have access to the raw information for this study are only limited to the researcher and the supervisors. Data collected will be stored in a password-protected computer and is only available to the researchers. Hard copy data (paper etc) will only be kept in the researcher's office and locked in a specific drawer/filing cabinet. All data will be stored according to ECU policy and regulations following the completion of the study.

Results of the Research Study

The results of this study are intended for completion of a Doctor of Philosophy thesis and may be presented in conferences/seminars and published in peer-reviewed journal(s), as magazine articles, as an online article or part of a book section and reports. Published results will not contain information that can be used to identify participants unless specific consent for this has been obtained. A copy of published results may be obtained by the participants upon request to the lead investigator (Andrew Walsh).

Voluntary Participation

Your participation in this study is voluntary. No monetary reward will be provided. No explanation or justification is needed if you choose not to participate. Your decision if you do not want to participate or continue to participate will not disadvantage you or involve any penalty.

Withdrawing Consent to Participate

You are free to withdraw your consent to further involvement in this research project at any time. You also have the right to withdraw any personal information that has been collected during the research with your withdrawal.

Questions and/or Further Information

If you have any questions or require more information about the research project, please do not hesitate to contact

Andrew Walsh
Office 21.501, School of Exercise, and Health Sciences, Edith Cowan University
270 Joondalup Drive, Joondalup, WA 6027 Australia.
Mobile: XXXXXXXXXX
Email: andrew.walsh@ecu.edu.au

Independent Contact Person

If you have any concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Kim Gifkins (Research Ethics Officer)
Building 1, Block 'B', Level 3, Room 333, Edith Cowan University, 100 Joondalup Drive, JOONDALUP WA 6027

Phone: (+61 8) 6304 2170
Email: research.ethics@ecu.edu.au
Website: http://www.ecu.edu.au/GPPS/ethics

Approval by the Human Research Ethics Committee:

This research project has been approved by the ECU Human Research Ethics Committee. Attached is the letter of approval for your information.

Appendix B- Information letter Study 2

Information Letter to Participants

Thank you very much for indicating your interest in participating in this study. The purpose of this document is to explain the study that you are going to participate. Please read carefully and understand the information below, and do not hesitate to ask any questions.

Project Title

Analysis of perceptual-motor calibration processes in indoor climbing

Researchers

This research project is being undertaken as part of the requirements of a Doctor of Philosophy (PhD, Sports Science) at Edith Cowan University (ECU).

PhD Student: Andrew Walsh (andrew.walsh@ecu.edu.au) 6304 3779

Supervisor: Dr. James Croft (j.croft@ecu.edu.au) 6304 2342

Co-Supervisor: A/Prof Chris Button (chris.button@otago.ac.nz) +64 3479 9122

Co-Supervisor: Prof Ludovic Seifert (ludovic.seifert@univ-rouen.fr)

Further details on supervisors and School of Exercise and Health Sciences are available at http://www.sebhs.ecu.edu.au.

Purpose of the study

We are interested in determining the influence of encumbrance position, load and maximal contraction influence the perception of reachability and graspability between climbers and non-climbers.

Eligibility

You will be eligible for this study if your age is between 16 and 45 yrs, have no history of major injury, have no significant vision problems, have no conditions that impede your ability to maintain balance and are injury free at the time of your participation in the study.

In addition to the above inclusion criteria, we will be testing two groups- climbers and non-climbers:

For climbers, you must have a minimum of two years climbing experience, be able to climb grades 24 or higher on the Australian Scale, be able to complete a chin up with 10% body mass attached.

For non-climbers, you must engage in regular physical activity at least twice per week (recreational or competitive) in the last 12 months, have not engaged in any rock climbing previously or be in an occupation that involves climbing, be able to complete a chin up with 10% body mass attached.

You will be screened with a generic medical questionnaire consisting of several questions about your health and physical conditions. Once you are found to be eligible for the study, you will be invited to participate as a subject in this study.

Requirements

You will be required to complete 5 sessions (1 familiarisation session, 4 testing sessions). All testing sessions will comprise of a 5 min bouldering warm up session followed by approximately 60-90 min testing session, where will you be required to give your perception of your maximal boundary from your starting position (foot holds 50cm off the ground). Maximal boundary of reach will be defined as the furthest point where you can touch the object while maintaining balance. Maximal boundary of grasp will be defined by the highest point where you can maintain hold of the object and still support your body mass. You will be required to determine your perceived grasp and reach while supporting yourself on a climbing wall. You be required to give perceptual estimates for 2 directions (left, and right) from a single-leg position, while being encumbered. For this study, an encumbrance of 10% of body mass will be used, with the weights being attached at hip or shoulder level, and a no-body mass (control) condition. You will give three (3) estimates for each direction for each condition (hip 10%, and shoulder 10%) and the no-body mass condition. You will give perceptions of grasp and reach with the start and target-hold both being a pinch grip (sessions 1 and 2 only). After you have successfully completed all estimates, you will undergo the maximal contraction protocol (Sessions 1-4; for protocol see below) under the hips 10% condition and no-body mass and redo the perceptual estimates for each direction. Maximal contraction will be defined as being unable to maintain contact with the hang-board at 90-degree elbow flexion and falling off. Once you have completed you will give your rating of perceived exertion and then be required to give your perception of your maximal boundary where you can maintain grasp and reach. You will be required to determine your perceived grasp and reach while on the wall, while keeping your hands on the starting hold. The mechanism will move according to your verbal commands until you believe you can no longer maintain a grasp/reach on the hold. Your actual boundary of grasp and reach will be obtained in the final session. You will be required to wear all rock climbing safety gear (harness, and shoes) for all testing sessions. You will be requested not to perform any strenuous exercise 2 days prior to the testing session and refrain from consuming caffeine and alcohol at least 12 hours prior to testing.

Familiarisation session

During familiarisation session you will be acquainted with all testing procedures, and where you will be positioned. To familiarise yourself with the sliding mechanism, a demonstration will be given on how it works, as well as the verbal instructions you will need to give.

Exercise

You (as the subject) will be required to be directly on the wall (foot holds 50cm off the ground) and assess whether you believe you can maintain grasp/ reach on a hold that is secured to a sliding mechanism. At the instant you believe you cannot maintain grasp or reach the hold, say stop. You will also be required to completed a maximal contraction protocol, where you will be asked to hold yourself at 90-degree elbow flexion for as long as possible. Each session will take approximately 60 to 90 minutes.

Equipment you will need

For this study you will need to bring your harness, rock climbing apparel, and rock climbing shoes.

Measurements

During the testing, we will be taking measurements of the height of where you believe you can no longer maintain grasp or reach the hold, and how long you can maintain the maximal contraction.

Testing Procedures

Body Position – Throughout the testing you will be required to assume a bimodal staring position. Bimodal represents one hand hold and one foot hold. For this condition, you will need to support yourself, and feet must maintain contact with the supporting foothold.

Single-leg starting position

Perception of Grasp/reach – You will be required to give your perception of grasp and reach when positioned on a wall. Your perception of grasp and reach will be determined by verbally instructing the lead investigator to move a sliding pole (see picture below)

Maximal contraction – You will be required to hang off a rock climbing training apparatus called a hang-board (see below). You will be loaded up with 10% of body mass and no-body mass (0%) prior to the contraction protocol. You will then be instructed to hold on as long as possible while maintaining an elbow flexion at 90 degrees. Mats will be placed underneath, and verbal encouragement will be provided.

Maximal contraction on hangboard

Risks

The risks associated with this study are minimal. These risks may include falling and muscle strain; however, the possibility for these risk are very low. The reduce muscle strain, a 5 minute warm up will be implemented, and you will be required to stretch before any exercise. To minimise any potential injuries from falls, mats will be placed underneath you. The participants will be instructed on how to brace for impact if they are to fall. They will be instructed to reduce the impact by absorbing the force with their outstretched arms and legs.

Benefits

You will gain insight into the research process and techniques, and will also gain information about your perception of the vertical environment. The results of this study will also be provided to you upon request.

Confidentiality of Information

All information provided by you will be treated with full confidentiality. Your contact information will only be accessible by the chief investigator during the period of the study. The information and data gathered from you during the study will be used to answer the research question of this study. People who will have access to the raw information for this study are only limited to the researcher and the supervisors. Data collected will be stored in a password-protected computer and is only available to the researchers. Hard copy data (paper etc) will only be kept in the researcher's office and locked in a specific drawer/filing cabinet. All data will be stored according to ECU policy and regulations following the completion of the study.

Results of the Research Study

The results of this study are intended for completion of a Doctor of Philosophy thesis and may be presented in conferences/seminars and published in peer-reviewed journal(s), as magazine articles, as an online article or part of a book section and reports. Published results will not contain information that can be used to identify participants unless specific consent for this has been obtained. A copy of published results may be obtained by the participants upon request to the lead investigator (Andrew Walsh).

Voluntary Participation

Your participation in this study is voluntary. No monetary reward will be provided. No explanation or justification is needed if you choose not to participate. Your decision if you do not want to participate or continue to participate will not disadvantage you or involve any penalty.

Withdrawing Consent to Participate

You are free to withdraw your consent to further involvement in this research project at any time. You also have the right to withdraw any personal information that has been collected during the research with your withdrawal.

Questions and/or Further Information

If you have any questions or require more information about the research project, please do not hesitate to contact

Andrew Walsh

Office 21.501, School of Exercise, and Health Sciences, Edith Cowan University

270 Joondalup Drive, Joondalup, WA 6027 Australia.

Mobile: [redacted]

Email: andrew.walsh@ecu.edu.au

Independent Contact Person

If you have any concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Kim Gifkins (Research Ethics Officer)

Building 1, Block 'B', Level 3, Room 333, Edith Cowan University, 100 Joondalup Drive, JOONDALUP WA 6027

Phone: (+61 8) 6304 2170

Email: research.ethics@ecu.edu.au

Website: http://www.ecu.edu.au/GPPS/ethics

Approval by the Human Research Ethics Committee:

This research project has been approved by the ECU Human Research Ethics Committee. Attached is the letter of approval for your information.

Appendix C- Information letter Study 3

Information Letter to Participants

Thank you very much for indicating your interest in participating in this study. The purpose of this document is to explain the study that you are going to participate. Please read carefully and understand the information below, and do not hesitate to ask any questions.

Project Title

Analysis of perceptual-motor calibration processes in indoor climbing

Researchers

This research project is being undertaken as part of the requirements of a Doctor of Philosophy (PhD, Sports Science) at Edith Cowan University (ECU).

PhD Student: Andrew Walsh (andrew.walsh@ecu.edu.au) 6304 3779

Supervisor: Dr. James Croft (j.croft@ecu.edu.au) 6304 2342

Co-Supervisor: A/Prof Chris Button (chris.button@otago.ac.nz) +64 3479 9122

Co-Supervisor: Prof Ludovic Seifert (ludovic.seifert@univ-rouen.fr)

Further details on supervisors and School of Exercise and Health Sciences are available at http://www.sebhs.ecu.edu.au.

Purpose of the study

We are interested in determining how continual exercise influences an individuals ability to calibrate to their environment and how this relates to changes in movement economy.

Eligibility

You will be eligible for this study if your age is between 16 and 45 yrs, have no history of major injury, have no significant vision problems, have no conditions that impede your ability to maintain balance and are injury free at the time of your participation in the study. You will be screened with a generic medical questionnaire consisting of several questions about your health and physical conditions. Once you are found to be eligible for the study, you will be invited to participate as a subject in this study.

Requirements

You will be required to complete 1 session which will comprise of a 5 min bouldering warm up session followed by a 60 to 90 min testing session, where will you be required to climb one route three times. For this study, exhausted will be when you are unable to maintain contact with a hang board and fall off. Prior to any climbing, you will have 70 markers placed on your body. After you have scaled the route, you will be required to hang off the hang board for as long as possible. Once you have completed you will be required to give a score of your fatigue on an RPE scale. Immediately after you will climb the same route. Once this is completed, you will be given 2 minutes rest and climb the route for the final time. You will be required to wear all rock-climbing safety gear (harness, and shoes) for all testing sessions. You will be requested not to perform any strenuous exercise 2 days prior to the testing session and refrain from consuming caffeine and alcohol at least 12 hours prior to testing.

Exercise

You (as the subject) will be required to climb one route three times under different levels of fatigue. For the exhaustion protocol, you will be required to hang onto a hang board for as long as possible. During the climbing we will be tracking your movements with motion analysis software. Each session will take approximately 60 to 90 minutes.

Equipment you will need

For this study you will need to bring your harness, rock climbing apparel, and rock climbing shoes.

Measurements

During the testing, we will be taking measurements of your rates of fatigue (RPE) and movement economy.

Testing Procedures

Belaying – Prior to climbing, you will be secured into a climbing safety mechanism (rope, harness, and anchor; see picture below). The rope will be controlled by a belayer who will ensure the rope is taut at all times to ensure the climbers safety.

Motion Capture (Vicon) – Prior to climbing, you will have a 7 markers placed all over your body (full body marker set; see Appendix A). This will allow us to determine and track your centre of mass (CoM). This will allow for the determination of movement economy during a climbing task.

Risks

The risks associated with this study are minimal. These risks may include a sore neck from looking up, falling and muscle strain; however, the possibility for these risk are very low. The reduce muscle strain, a 5 minute warm up will be implemented, and you will be required to stretch before any exercise. To minimise any falls, you will be climbing top rope style that includes being securing a rope to your harness which will connected to an experienced belayer, who is using a gri-gri, via an anchor at the top of the climb. This system ensures any falls that are experienced are minimal (few cm). Finally, the participants will be instructed on how to brace for impact if they are to fall. They will be instructed to reduce the impact by absorbing the force with their outstretched arms and legs.

Benefits

You will gain insight into the research process and techniques, and will also gain information about your perception of the vertical environment. The results of this study will also be provided to you upon request.

Confidentiality of Information

All information provided by you will be treated with full confidentiality. Your contact information will only be accessible by the chief investigator during the period of the study. The information and data gathered from you during the study will be used to answer the research question of this study. People who will have access to the raw information for this study are only limited to the researcher and the supervisors. Data collected will be stored in a password-protected computer and is only available to the researchers. Hard copy data (paper etc) will only be kept in the researcher's office and locked in a specific drawer/filing cabinet. All data will be stored according to ECU policy and regulations following the completion of the study.

Results of the Research Study

The results of this study are intended for completion of a Doctor of Philosophy thesis and may be presented in conferences/seminars and published in peer-reviewed journal(s), as magazine articles, as an online article or part of a book section and reports. Published results will not contain information that can be used to identify participants unless specific consent for this has been obtained. A copy of published results may be obtained by the participants upon request to the lead investigator (Andrew Walsh).

Voluntary Participation

Your participation in this study is voluntary. No monetary reward will be provided. No explanation or justification is needed if you choose not to participate. Your decision if you do not want to participate or continue to participate will not disadvantage you or involve any penalty.

Withdrawing Consent to Participate

You are free to withdraw your consent to further involvement in this research project at any time. You also have the right to withdraw any personal information that has been collected during the research with your withdrawal.

Questions and/or Further Information

If you have any questions or require more information about the research project, please do not hesitate to contact

Andrew Walsh
Office 21.501, School of Exercise, and Health Sciences, Edith Cowan University
270 Joondalup Drive, Joondalup, WA 6027 Australia.
Mobile: XXXXXXXXXX

Email: andrew.walsh@ecu.edu.au

Independent Contact Person

If you have any concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Kim Gifkins (Research Ethics Officer)

Building 1, Block 'B', Level 3, Room 333, Edith Cowan University, 100 Joondalup Drive, JOONDALUP WA 6027

Phone: (+61 8) 6304 2170

Email: research.ethics@ecu.edu.au

Website: http://www.ecu.edu.au/GPPS/ethics

Approval by the Human Research Ethics Committee:

This research project has been approved by the ECU Human Research Ethics Committee. Attached is the letter of approval for your information.

Appendix D- Informed consent

Informed Consent Form

Project: Analysis of perceptual-motor calibration processes in indoor climbing

I have read the information sheet and understood the points in the informed consent form. I agree to participate in this study with the above title and give my consent freely. I understand that the study will be carried out as described in the information sheet, a copy of which I have retained. I realise that whether or not I decide to participate is my decision. I also realise that I can withdraw from the study at any time and that I do not have to give any reasons for withdrawing. I have had all questions answered to my satisfaction.

Name: ____________________________________ Date: ___________________

Signature: _________________________________

Parent/ Guardian (only if applicable)

I, ____, as parent / guardian of Mr/ Miss ____, acknowledge that I have read and understood the information sheet and hereby give permission for my child to participate in the study

Signature: ____________________________________

Date (DD/MM/YYYY): _________________________

Appendix E- General Medical Questionnaire

Pre-exercise Medical Questionnaire

The following questionnaire is designed to establish a background of your medical history, and identify any injury and/ or illness that may influence your testing and performance. If you are under 18 then a parent or guardian should complete the questionnaire on your behalf or check your answers and then sign in the appropriate section to verify that they are satisfied the answers to all questions are correct to the best of their knowledge.

Please answer all questions as accurately as possible, and if you are unsure about anything please ask for clarification. All information provided is strictly confidential.

Personal Details

Name:____

Date of Birth (DD/MM/YYYY):_________________ Gender: Female/ Male

PART A

If YES, please provide details

1. Are you a regular smoker or have you quit in the last 6 months?	Y	N		______________
2. Did a close family member have heart disease or surgery, or stroke before the age of 60 years?	Y	N	Unsure	______________
3. Do you have, or have you ever been told you have blood pressure above 140/90 mmHg, or do you current take blood pressure medication?	Y	N	Unsure	______________

4. Do you have, or have you ever been told you have, a total cholesterol level above 5.2 mmol/L (200 mg/dL)? Y N Unsure ________________

5. Is your BMI (weight/height^2) greater than 30 kg/m^2? Y N Unsure ________________

PART B

1. Have you ever had a serious asthma attack during exercise? Y N ______________________

2. Do you have asthma that requires medication? Y N ______________________

3. Have you had an epileptic seizure in the last 5 years? Y N ______________________

4. Do you have any moderate or severe allergies? Y N ______________________

5. Do you, or could you reasonably, have an infectious disease? Y N ______________________

6. Do you, or could you reasonably, have an infection or disease that might be aggravated by exercise? Y N ______________________

7. Are you, or could you reasonably be, pregnant? Y N ______________________

PART C

1. Are you currently taking any prescribed or non-prescribed medications?

	Y	N	____________________

2. Have you had, or do you currently have, any of the following?

			If YES, please provide details
Rheumatic fever	Y	N	____________________
Heart abnormalities	Y	N	____________________
Diabetes	Y	N	____________________
Epilepsy	Y	N	____________________
Recurring back pain that would make exercise problematic, or where exercise may aggravate the pain	Y	N	____________________
Recurring neck pain that would make exercise problematic, or where exercise may aggravate the pain	Y	N	____________________
Any neurological disorders that would make exercise problematic, or where exercise may aggravate the condition	Y	N	____________________
Any neuromuscular disorders that would make exercise problematic, or where exercise may aggravate the condition	Y	N	____________________
Recurring muscle or joint injuries that would make exercise problematic, or where exercise may aggravate the condition	Y	N	____________________
A burning or cramping sensation in your legs when walking short distances	Y	N	____________________

Chest discomfort, unreasonable breathlessness, dizziness or fainting, or blackouts during exercise	Y	N	____________________

PART D

Have you had flu in the last week?	Y	N	____________________
Do you currently have an injury that might affect, or be affected by, exercise?	Y	N	____________________

*Is there any other condition not previously mentioned that may affect your ability to participate in this study?

Y N ____

Declaration (to be signed in the presence of the researcher)

I acknowledge that the information provided on this form, is to the best of my knowledge, a true and accurate indication of my current state of health.

Participant

Name:________________________ Date (DD/MM/YYYY):_______________

Signature:____________________________

Researcher:

Signature:_____________________________

Date (DD/MM/YYYY):_________________

Parent/ Guardian (only if applicable)

I, ____, as parent / guardian of Mr/ Miss ____, acknowledge that I have checked the answers provided to all questions in the medical questionnaire and verify that they are correct to the best of my knowledge.

Signature: ____________________________________

Date (DD/MM/YYYY): _________________________

Practitioner (only if applicable)

I, Dr _______________________________________ have read the medical questionnaire and information/ consent form provided to my patient Mr/Miss/ Ms____________________________________, and clear him/ her medically for involvement in exercise testing.

Signature:______________________________________

Date (DD/MM/YYYY):__________________________

Emergency Contact Details

Project Details: Analysis of perceptual-motor calibration processes in indoor climbing

Emergency Contact for: ____

Next of Kin: Name: ______________________________________

Daytime Contact: ____________________________

After Hours Contact: _________________________

Mobile Number: _____________________________

Relationship: _______________________________

Appendix F- Climbing Experience Questionnaire

Climbing Experience Questionnaire

The following questionnaire is designed to establish a background of your climbing history that will aid with our testing procedures. Please answer all questions as accurately as possible, and if you are unsure about any thing please ask for clarification. All information provided is strictly confidential.

Name: ____

Date of Birth (DD/MM/YYYY):_______________ Gender: Female/ Male

Years of Climbing Experience:___________

Highest Top Rope grade completed (in last 6 months):__________

Preferred climbing style: Top Rope/ Boulder/ Lead

Amount of hours training per week:_____________

Declaration (to be signed in the presence of the researcher)

I acknowledge that the information provided on this form, is to the best of my knowledge, is true and accurate.

Participant

Name:_______________________ Date (DD/MM/YYYY):______________

Signature:___________________________

Researcher

Name:________________________ Date (DD/MM/YYYY):_______________

Signature:____________________________

Parent/ Guardian (only if applicable)

I, ____, as parent / guardian of Mr/ Ms ____, acknowledge that I have checked the answers provided to all questions in the questionnaire and verify that they are correct to the best of my knowledge.

Signature: ____________________________________

Date (DD/MM/YYYY): _________________________

Appendix G- Exercise History Questionnaire

Exercise History Questionnaire

The following questionnaire is designed to establish your exercise history background and this will aid with our testing procedures. Please answer all questions as accurately as possible, and if you are unsure about any thing please ask for clarification. All information provided is strictly confidential.

Name: ____

Date of Birth (DD/MM/YYYY):_____________ Gender: Female/ Male

Have you participated in any sport within the last 12 months? Y / N

If yes provide details below

____

____

Have you participated in any exercise in the last 12 months? Y / N

If yes provide details below

____

____

What is your job and does it require any physical activity (running, cycling, climbing)?

Y / N

If yes provide details below

____

____

Declaration (to be signed in the presence of the researcher)

I acknowledge that the information provided on this form, is to the best of my knowledge, is true and accurate.

Participant

Name:________________________ Date (DD/MM/YYYY):_______________

Signature:____________________________

Researcher

Name:________________________ Date (DD/MM/YYYY):_______________

Signature:____________________________

Parent/ Guardian (only if applicable)

I, ____, as parent / guardian of Mr/ Ms ____, acknowledge that I have checked the answers provided to all questions in the questionnaire and verify that they are correct to the best of my knowledge.

Signature: ____________________________________

Date (DD/MM/YYYY): _________________________

Appendix H- Media Release Form

Photo, Video, and Audio Consent and Release Form

During the data collection period for the project labelled "Analysis of perceptual-motor calibration process in indoor climbing", video, audio and photo data will be collected. Edith Cowan University as well as the author affiliated with the aforementioned study, requests the right to use all such photos, videos, print material and audio taken from the youth and adults involved in this project. They may be used for a variety of purposes, included, but not limited to, publications, conferences/seminars, online article/books, disclosed to any third party that has aided in the data collection (e.g. coaching staff/development officers), and other similar lawful purposes.

By signing this I consent and give permission to allow Edith Cowan University and the author affiliated with the project labelled "Analysis of perceptual-motor calibration process in indoor climbing" the unlimited right to use the photos, video and audio clips that they have of me/my child participating in this study. I agree to give up my rights with regards to Edith Cowan University and the affiliated authors video, photo and audio clips of me/my child collected from the aforementioned study. Further, by signing the consent and release form, I acknowledge that I understand and agree to the above request and conditions. I sign this form freely and without inducement.

Name: ____________________________________ Date: ___________________

Signature: _________________________________

-

Parent/ Guardian (only if applicable)

I, ____, as parent / guardian of Mr/ Miss ____, acknowledge that I have read and understood the information sheet and hereby give permission for my child to participate in the study

Signature: ____________________________________

Date (DD/MM/YYYY): _________________________