**Recalibration in functional perceptual-motor tasks: a systematic review**

Milou Tessa Brand\* and Rita Ferraz de Oliveira

Sport and Exercise Science Research Centre, School of Applied Sciences, London South Bank University, 103 Borough Rd, SE1 0AA London, United Kingdom

\*Corresponding author:

Milou Tessa Brand

Phone number: 020 7815 7909

E-mail: [m.brand@lsbu.ac.uk](mailto:m.brand@lsbu.ac.uk)

Funding:

This work was supported by London South Bank University under the Building our Environment Grant.

Author’s note:

Preliminary results of this study were presented at the European Workshop on Ecological Psychology July 2016.

**Manuscript accepted for publication on 28/10/2017 in Human Movement Science**

**Recalibration in functional perceptual-motor tasks: a systematic review**

**Abstract**

Skilled actions are the result of a perceptual-motor system being well-calibrated to the appropriate information variables. Changes to the perceptual or motor system initiates recalibration, which is the rescaling of the perceptual-motor system to informational variables. For example, a professional baseball player may need to rescale their throws due to fatigue. The aim of this systematic review is to analyse how recalibration can and has been measured and also to evaluate the literature on recalibration. Five databases were systematically screened to identify literature that reported experiments where a disturbance was applied to the perceptual-motor system in functional perceptual-motor tasks. Each of the 91 experiments reported the immediate effects of a disturbance and/or the effects of removing that disturbance after recalibration. The results showed that experiments applied disturbances to either perception or action, and used either direct or indirect measures of recalibration. In contrast with previous conclusions, active exploration was only sufficient for fast recalibration when the relevant information source was available. Further research into recalibration mechanisms should include the study of information sources as well as skill expertise.

**Keywords:** recalibration; scaling; perception; action; ecological psychology

1. **Introduction**

Imagine you are a major league baseball pitcher expected to throw a strike ball each time you pitch. Halfway through the game your arm is getting slightly fatigued but you are expected to keep throwing your pitches. Your next throw may be a little off or outside the strike zone but you soon find the right adjustments and throw the ball accurately again. “Getting used to the fatigue” includes the rescaling of both the perceptual and the motor system and this process is known as *recalibration* (Withagen & Michaels, 2004, 2007). The aim of this systematic review is to analyse how recalibration can and has been measured and also to evaluate the literature on recalibration.

In the present review, recalibration has been defined in the context of the ecological approach. According to this approach, people directly detect the useful information available in the environment to guide their actions (J J Gibson, 1979). The proposal is that people do not detect the intrinsic properties of objects, but rather the informational variables that are specified by actions. That is to say, the information that is available in the environment is directly useful to guide the actions performed. In the context of ecological psychology, the accuracy of actions can be improved using attunement, calibration, and recalibration which we will define next (Jacobs, Vaz, & Michaels, 2012; Michaels & Carello, 1981; Withagen & Michaels, 2004).

From an ecological perspective, it has been proposed that during attunement, the person converges onto the most useful informational variable(s) that are available and can guide a successful action. Actions can be inaccurate because the person converged onto variables that are not optimal, meaning that they are not sufficiently specifying for a given action (Jacobs et al., 2012). However, through exploration, they may attune to those variables which result in consistently good performance (Michaels & Carello, 1981). For example, throwing to a target can be specified by variables that relate directly to the distance to the target such as the angle of elevation or declination (de Oliveira, Oudejans, & Beek, 2009; Ooi, Wu, & He, 2001). The attunement process by which people gradually change from detecting less useful to more specifying variables is also referred to as education of attention (Gibson, 1963; Gibson & Gibson, 1955; Jacobs et al., 2012). Attunement on its own may not always be sufficient because calibration is also required for actions to be successful (Withagen & Michaels, 2004).

Calibration is the second process involved in improving the accuracy of actions. From an ecological perspective, calibration is defined as the scaling of action to the perceptual information (Withagen & Michaels, 2004). Having attuned to using certain informational variables the person needs, subsequently, to scale their perception-action link to these informational variables. This calibration is only possible through practice and it is what maintains the appropriate relation between the informational variable and the perception or action (e.g., Jacobs & Michaels, 2006; Withagen & Michaels, 2002, 2004). In spite of important differences, the term calibration has often been used interchangeably with recalibration including in the only review on [re]calibration by van Van Andel, Cole and Pepping (2017). This may have been because certainly they are thought to be similar processes of scaling information to perception and action. The distinction is important, however, because they differ in terms of: a) what may elicit these processes; b) how long they may take to complete; c) what methods should be used to investigate them; and d) practical implications when calibration or recalibration are thought to underlie poor performance.

Recalibration happens only after a *disturbance* in either perception or action renders the perception-action link inaccurate, thereby initiating the rescaling of that link (rearrangement). For example, when a player’s throwing requires an updated scaling of the perceptual-motor coupling due to fatigue. Recalibration is necessary to cope with different environments, using different tools, and coping with acute and long-term changes within the musculoskeletal system. Recalibration has been thought to largely depend on exploration (Withagen & Michaels, 2004, 2007) and a recent review concluded that even minimal movements may be sufficient for recalibration (Van Andel et al., 2017). The authors stated that recalibration occurred rapidly when there was a good match between the action that required recalibration and the movements that participants were allowed to make during exploration (e.g., when exploring maximal braking capabilities by experiencing braking in a car). On the other hand, when movements were restricted recalibration took longer. These conclusions were based on 4 articles and applied only to changes in action capabilities, so it is unclear whether the authors’ generalization is warranted. Another review studied only changes in perception and consequent recalibration using prism glasses (Redding, Rossetti, & Wallace, 2005). They studied recalibration in a three-step process: a pre-exposure baseline, an active exposure to the prism glasses, and a post-exposure after-effect. In the present systematic review, we will review recalibration by including experiments that studied changes in both perception and action and we also include all the stages relevant for the study of recalibration.

--------- Insert figure 1 about here ---------

Recalibration is a dynamic process that can be captured and measured at different points in time. Schematically, recalibration consists of five different measurable stages that can be useful to guide research into the process of recalibration. We propose Figure 1 as an illustration of the recalibration process (extended from Redding, Rossetti, & Wallace (2005)). It includes a (1) *baseline* where the perception-action coupling is calibrated for a given task. Measurement at baseline is crucial to establish that the skill is well-calibrated. A (2) *disturbance* in the perception-action coupling where performance is affected. This can be a disturbance directed at the action system or the perceptual system. After this, the (3) *rearrangement* period consists of rescaling perception and action to information. During this period performance can be measured trial-by-trial to capture for example whether recalibration is gradual or sudden. At (4) *removal* the disturbance is withdrawn and performance is affected again (often known as after-effect). The (5) *post-rearrangement* period consists of rescaling perception and action back to baseline levels. Again, trial-by-trial measurements can ascertain the time course of this stage. Different studies have measured different stages of this model. For example, Scott and Gray (2010) focused on measuring the *disturbance* and *rearrangement* of perception-action to study recalibration. In their study, participants used either a standard, lighter or heavier bat to swing at a simulated approaching baseball. During the first couple of trials, significant differences were found in baseball swings between the three bat conditions (*disturbance*). The lighter group *rearranged* within five pitches and the heavier group *rearranged* within 10 pitches. After 30 trials, differences between the three groups were not significant, hence rearrangement was complete. Alternatively, Kunz, Creem-Regehr, and Thompson (2015) took measurements at the *baseline* and *removal* to study recalibration. Participants walked through a visually faster or a visually slower hallway (*disturbance*). After *removal* of this visual disturbance, they measured an after-effect whereby participants overshot distance in the visually slower condition and undershot distance in the visually faster condition.

An additional strategy used to study the concept of recalibration is to investigate whether the rearrangement of the perception-action coupling for one action transfers to another action. In studying how the transfer of recalibration is organised, Rieser, Pick Jr, Ashmead, and Garing (1995) found that the rearrangement of walking transferred to side-stepping which served the same functional goal but did not transfer to throwing. The authors argued that this type of functional organisation is most efficient because recalibrating one action to a particular environmental situation generalises to other actions which may be used to accomplish the same goal (Rieser et al., 1995). On the other hand, Bingham, Pan, and Mon-Williams (2014) studied anatomical recalibration which had also been proposed by Rieser et al. (1995). Bingham et al. (2014) argued that the transfer of recalibration should also be anatomical because there are often anatomical differences between limbs (e.g., one arm shorter than the other). They proposed that where the anatomy of limbs is different, the recalibration of actions by one limb should affect the other limb (Bingham et al., 2014).

The aim of this systematic review is to analyse how recalibration can and has been measured and also to evaluate the literature on perceptual-motor recalibration. Although previous reviews have been published on the topic of recalibration, they have not 1) addressed the methodological strategies used in those studies and 2) have been restrictive in terms of type of disturbance included. In this connection, there are two reviews worth mentioning. The first is a recent review by Van Andel et al. (2017) who studied disturbances to action capabilities only; they concluded that active exploration was necessary for [re]calibration and that there was no research on older populations. The second review, by Redding et al. (2005), studied only disturbances to perception using prism glasses. Currently no review has focused on experiments that included disturbances applied to both the perceptual and the motor systems. This is important because the concept of recalibration entails the recoupling of perception and action based on information. Therefore, if we find that recalibration is essentially different depending on which system is primarily affected by the disturbance, this has implications for the concept of recalibration. Currently there is no information available regarding the methods, measures and results across these disturbances. Therefore, this systematic review studies disturbances that are applied to both the perceptual and the motor systems in functional perceptual-motor tasks. The analysis of these experiments focusses on how recalibration can and has been measured, and on evaluating the literature on recalibration.

1. **Methods**

***2.1 Search strategy***

An extensive literature search was performed using the following electronic databases: Medline, Web of Science, Scopus, SportDiscus and PsycInfo. The following search terms were used: [perceptual-motor OR ecological psychology] AND [movement OR locomotion OR exercise OR action] AND [calibrat\* OR recalibrat\* OR adapt\* OR readapt\* OR scale OR rescale OR scaling]. The search was performed on all available literature up to December 2016 and limited to experimental articles written in English. The authors also manually screened the literature for additional relevant articles.

***2.2 Inclusion and exclusion criteria***

The literature was screened based on titles, abstracts and full-texts to include relevant articles. For inclusion, articles had to report on experiments where a disturbance was applied to the perceptual-motor system in a task that involved functional perceptual-motor tasks. Articles had to report data on the immediate effect of a disturbance or removal as well as include an additional data point to compare it against. For example, this could be data on disturbance and rearrangement, or baseline and removal (see Figure 1). Articles had to report on participants who were healthy and with normal or corrected-to-normal vision. Articles were excluded if their focus was on attunement (or learning) instead of recalibration, if the task involved pacing to an external rhythm, or if it was based on eye-movement data only. Articles were also excluded if their focus was on sensorimotor adaptation, or the disturbance was to proprioception. Both authors reviewed the search results independently in three phases; first the titles, then abstracts, and then full texts. For each phase, in case of disagreement, the conflicting article was discussed until a consensus was reached over its inclusion or exclusion.

Figure 2 shows the results of the review phases in a flow diagram (PRISMA; Moher, Liberati, Tetzlaff, & Altman, 2009). The database search resulted in the retrieval of 1773 journal articles of which 192 duplicates were removed. The remaining 1581 articles were screened for their titles and subsequently 467 titles were selected for abstract screening. There were 86 articles identified as potentially relevant based on their abstracts and their full-text articles were reviewed. In addition, the authors screened the literature and included 4 articles for full-text review. A final list of 44 articles was identified as suitable for inclusion in the systematic review; these articles included a total of 91 experiments.

--------- Insert figure 2 about here ---------

***2.3 Quality assessment***

Table 1 shows the scale for the quality assessment of the experiments. We adapted a scale with items from both the Quality Index (Downs & Black, 1998) and the Crowe Critical Appraisal Tool (Crowe & Sheppard, 2011), and added two relevant items for assessing recalibration experiments (adaptations have been used before e.g., Uiga, Cheng, Wilson, Masters, & Capio, 2015; Van Andel et al., 2017). The scores for each of the items on the scale ranged from: 0 = no information, 1 = unclear or incomplete, and 2 = clear and detailed. The maximum score available for the quality assessment was 24.

--------- Insert table 1 about here ---------

The mean score for the methodological quality of the experiments was 73 % (SD = 10 %) with a range of 46-92 % (see Table 2). More than 92 % of the experiments clearly described their study design, procedure, tasks, data collection and results. Detailed information on participants’ characteristics and the inclusion of a control group was only found, respectively, in 49 % and 11 % of the experiments.

--------- Insert table 2 about here ---------

1. **Results**

***3.1 Descriptive statistics***

The number of studies on recalibration has steadily grown over the years after the first articles were published in 1985. Most recalibration studies were published in the Journal of Experimental Psychology: Human Perception and Performance (39 %), followed by Experimental Brain Research (17 %) and Ecological Psychology (16 %). Half of the recalibration articles reported multi-experimental articles (55 %) with two or more experiments. Only 29 % of the studies measured recalibration at 3 or more points during the recalibration process. The 38 % of experiments that reported participants’ characteristics recruited mainly university students. Overall, the age range in the studies was 18-52 years.

***3.2 Disturbances to perception or action and related measures***

Direct measures of recalibration are those where data is collected throughout the rearrangement period. These experiments (n = 50 out of 91) provided information on how long it took participants to rearrange and/or whether participants fully recalibrated to the disturbance. From these, half of the experiments (n = 25) applied a disturbance to the action capabilities of participants, for example by altering body dimensions and/or joint kinematics (e.g., attaching blocks underneath feet, holding wide objects, or being seated in a wheelchair; Franchak & Adolph, 2014; Hackney, Cinelli, & Frank, 2014; Higuchi, Takada, Matsuura, & Imanaka, 2004; Hirose & Nishio, 2001; Mark, 1987; Mark, Balliett, Craver, Douglas, & Fox, 1990; Scott & Gray, 2010; Stefanucci & Geuss, 2010; Stoffregen, Yang, & Bardy, 2005; Van Hedel & Dietz, 2004; Yasuda, Wagman, & Higuchi, 2014; Yu, Bardy, & Stoffregen, 2011; Yu & Stoffregen, 2012). For example, Van Hedel and Dietz (2004) measured gait pattern on 50 trials after attaching an orthosis to participants’ left foot. The other half of the experiments (n = 25) took direct measures of recalibration after applying a disturbance to perception (Bingham & Mon-Williams, 2013; Bingham & Romack, 1999; Bingham, Pan, & Mon-Williams, 2014; Bingham, 2005; Bingham & Pagano, 1998; Coats, Pan, & Bingham, 2014; Fernández-Ruiz & Díaz, 1999; Fortis, Ronchi, Calzolari, Gallucci, & Vallar, 2013; Mon-Williams & Bingham, 2007; Pagano & Bingham, 1998; Richter et al., 2002; Saunders & Durgin, 2011; Turchet, Camponogara, & Cesari, 2014). These experiments used prism glasses, restrictive monocular apparatus, virtual reality, or auditory information to disturb the participants’ perception. For example, Saunders and Durgin (2011) measured mean heading errors on 20 trials after disturbing visual heading through virtual reality.

Indirect measures of recalibration are those where data is collected before and after, but not during, the rearrangement period. These experiments (n = 41 out of 91) typically informed on the after-effects as a proxy to the preceding rearrangement period. The majority of experiments (n = 27) applied a disturbance to perception by manipulating optic flow, using prism glasses, or giving distorted feedback during the rearrangement period, and subsequently measuring effects upon removal of the disturbance (Bruggeman, Pick, & Rieser, 2005; Dotov, Frank, & Turvey, 2013; Kunz, Creem-Regehr, & Thompson, 2009, 2013; Kunz et al., 2015; Marcilly & Luyat, 2008; Mohler, Thompson, Creem-Regehr, & Willemsen, 2007; Redding & Wallace, 1985, 1987; Rieser et al., 1995; Wagman & Abney, 2012; Waller & Richardson, 2008; Withagen & Michaels, 2002, 2007). For example, Kunz, Creem-Regehr, & Thompson (2009) found that participants overshot distance by 15 % after walking in a visually slower environment and undershot distance by 14 % after walking in a visually faster environment. Fewer experiments (n = 7) took indirect measures of recalibration after manipulating action (Brennan, Bakdash, & Proffitt, 2012; Durgin et al., 2005; Rieser et al., 1995). These experiments disturbed different components of locomotion on a treadmill, such as duration and speed. For example, results showed that blind-walking distance significantly increased after only 20 seconds of treadmill blind-running (Durgin et al., 2005, study 6).

***3.3 The analysis of rearrangement phase***

Some experiments studied the rearrangement phase using a regression analysis where the slope and intercepts of these regression lines to show offset and inform about the scaling and offset of errors (n = 27; Bingham, 2005; Bingham & Pagano, 1998; Bingham & Romack, 1999; Coats et al., 2014; Mark, 1987; Mark et al., 1990; Mon-Williams & Bingham, 2007; Stoffregen et al., 2005; Wagman & Abney, 2012; Withagen & Michaels, 2007; Yu & Stoffregen, 2012). The intercept indicates an offset error; a constant underestimation or overestimation, for example of the actual distance. The slope indicates the scaling error, for example between perceived to actual distance. Bingham’s studies used slopes and intercepts to analyze the effect of distorted feedback on reaching movements (Bingham, 2005; Bingham & Pagano, 1998; Bingham & Romack, 1999; Coats et al., 2014; Mon-Williams & Bingham, 2007). These studies plotted reached distances against actual target distances and analysed the resulting slopes. Withagen and Michaels (2007) analysed the intercepts and slopes of the regression lines between perceived and actual length judgements. They used this pre-test slope to manipulate the feedback distortion and then tested whether recalibration transferred from length perception to sweet-spot perception. Similar methods were used by Wagman and Abney (2012) who compared intercepts and slopes in pre-test and post-test to evaluate the effects of distorted feedback. Other experiments also used slopes to indicate the change of judgement error over blocks or trials (Mark, 1987; Mark et al., 1990; Yu & Stoffregen, 2012).

***3.4 Quality and duration of the rearrangement period***

Results showed that active exploration was the most effective way to recalibrate to changes in perception or action capabilities (n = 15) as shown in Table 3. From these experiments, seven showed that a small amount of rearrangement trials (5 to 12 trials) was sufficient for complete or near-complete recalibration using a trial-by-trial rearrangement analysis. For example, Scott and Gray (2010, exp. 1) showed that participants recalibrated within five pitches to a lighter baseball bat, while participants using heavier bats recalibrated within 10 pitches. Bruggeman et al. (2005) found that participants throwing beanbags while rotating on a carousel recalibrated after 10 throws. Similarly, Bingham and Romack (1999) showed that participants placing an object in a target hole while wearing 10-diopter prism glasses recalibrated as their movement times gradually decreased over trials within each block. They also found that the initial effect of the disturbance gradually decreased over three days as recalibration took 10.2 trials on day 1 and was reduced to 5.6 trials on day 3. Other experiments also found that participants required a small amount of rearrangement trials before recalibrating (Mark, 1987; Mark et al., 1990; Saunders & Durgin, 2011; Scott & Gray, 2010).

From the 15 experiments, five also showed that participants recalibrated within 20-50 trials by setting a fixed amount of rearrangement trials for participants to rearrange. Note that shorter periods might have been sufficient but there was no trial-by-trial analysis of the rearrangement period. For example, 20 rearrangement trials squeezing through doorways while wearing a pregnancy pack dramatically reduced judgement errors of passibility (Franchak & Adolph, 2014, exp. 3). In another experiment, judgments also improved after 21 rearrangement trials during which participants walked through apertures with a 69-cm horizontal bar (Yasuda et al., 2014, exp.1). Other experiments also used a fixed amount of rearrangement trials during which recalibration occurred (Fortis et al., 2013; Hackney et al., 2014; Richter et al., 2002; Van Hedel & Dietz, 2004).

Interestingly, incomplete recalibration using active exploration was found in 8 experiments. The pattern seems to show that restricted availability of information during exploration resulted in a reduced ability to recalibrate. These experiments (n=5; Bingham, 2005; Bingham & Pagano, 1998) restricted visual perception in different conditions, but allowed participants to actively reach to a target. Their results showed that normal binocular vision resulted in an accurate perception of distance while monocular vision resulted in incomplete recalibration even with feedback (Bingham, 2005; Bingham & Pagano, 1998, exp.4). Furthermore, when participants viewed through a restrictive camera, they were unable to use the haptic feedback of reaching to improve performance (Bingham & Pagano, 1998, exp.3).

Secondly, incomplete recalibration was also found in experiments that used a wheelchair for locomotion (n=3, Higuchi et al., 2004, exp. 1-2; Yasuda et al., 2014). These experiments asked participants to make judgements about the person-plus-wheelchair passibility through apertures. Yasuda et al. (2014, exp.2) found that 21 rearrangement trials propelling a wheelchair through apertures were not sufficient to accurately judge passibility through apertures, and Higuchi et al. (2004, exp. 1) found that 20-28 rearrangement trials were also not sufficient. A longer period of rearrangement over eight days was effective in reducing participants’ underestimations after wheelchair-use on four separate days (Higuchi et al., 2004, exp. 2). It is noteworthy that although participants had normal locomotion and passibility experience, they had no prior experience with wheelchairs. Therefore, it is likely that the lack of experience or skill in the specific task of wheelchair passibility led to incomplete recalibration.

Recalibration without active exploration was not impossible, but it depended on the amount of restriction that was applied during the rearrangement period (n = 9; Mark, 1987; Mark et al., 1990; Stoffregen et al., 2005; Yu et al., 2011; Yu & Stoffregen, 2012). For example, when participants were allowed body sway during rearrangement but were not allowed to walk with blocks under their feet, they still recalibrated within 12 trials in a judgement task that depended heavily on eye-height as an information source (Mark, 1987, exp.3; Mark et al., 1990, exp.2; Stoffregen et al. 2005). In contrast, experiments where movement was severely restricted in a way that the restricted the availability of relevant information sources for the task, showed that participants did not recalibrate (Mark et al. 1990, exp. 3, 4, 5). Even when participants were allowed to move (e.g., by sitting 2-3 times) before performing a perceptual task under severe restrictions, participants did not recalibrate (Mark et al., 1990, exp. 6). In addition, experiments found that judgments about minimum lintel height when participants were allowed to move their head unrestrained were more accurate than when their heads were restrained during rearrangement (Yu et al., 2011; Yu & Stoffregen, 2012). These experiments indicate that the availability of information rather than the ability to move during the rearrangement is the crucial factor for rearrangement to be successful.

--------- Insert table 3 about here ---------

***3.5 The effects of disturbances on rearrangement***

Results suggest there may be a positive link between the disturbance effect and the time required to rearrange (n = 2). One experiment found that rearrrangement was longer for glasses of 30 prism diopter compared to glasses of 10 or 20 prism diopter (Fernández-Ruiz & Díaz, 1999, exp. 1). While participants reached maximum rearrangement with 30 diopter glasses within 12 throws, with 10 and 20 diopter glasses they only required 6 and 9 throws. Similarly, Van Hedel and Dietz (2004) found that more restrictive orthoses required longer rearrangement periods. Their experiment showed that participants fitted with an ankle-foot orthosis rearranged within 50 trials but this was not sufficient for participants fitted with a knee orthosis or knee-ankle-foot orthosis.

There is also some evidence (n=2) that longer rearrangement periods lead to longer post-rearrangement periods. Fernández-Ruiz and Díaz (1999, exp. 3) had two groups wearing 30 diopter prism glasses. One group had a rearrangement period of 25 throws at a target and the second group had a rearrangement period of 50 throws at a target. Although the after-effect upon removal of the prism glasses was similar in both groups, the post-rearrangement period required was longer for the group which had experienced a longer rearrangement period. Similarly, Bingham and Mon-Williams (2013) asked participants to reach and grasp a virtual target over 14-blocks or 24-blocks of distorted feedback. After removal of the (distorted) haptic feedback the 24-block group continued to show distorted reaches for another 6 blocks whereas the 14-block group immediately started reaching closer to the actual (undistorted) target.

There is contradictory evidence regarding the effect of the rearrangement period on the after-effect upon removal. While Fernández-Ruiz and Díaz (1999, exp. 3) used different rearrangement periods but found similar after-effects, Durgin et al. (2005, exp. 3, 6) also used different rearrangement periods but found different after-effects. Durgin et al. (2005, exp. 6) found that after 20 s of blind treadmill walking participants overshot a target during blind-walking by 12 %, and with an additional 40 s, 60 s, 80 s, and 100 s this increased to 18 %, 17 %, 22 %, and 21 % (Durgin et al., 2005, exp. 6). In another experiment, they found that the forward drift after-effect of blind running-in-place was significantly larger after two minutes blind treadmill running than after one minute blind-treadmill running (Durgin et al., 2005, exp.2)

* 1. ***Transfer of recalibration***

In total, 12 experiments studied whether the transfer of recalibration is functional, anatomical or both. In their experiment Bingham, Pan, and Mon-Williams (2014, exp. 2) showed an example of *anatomical* or limb-specific recalibration. The results showed that after 26 feedback blocks of reaching and grasping to a distorted virtual target simultaneously for both hands, the left hand overreached the target compared to the right hand after the feedback was removed. This indicated that although the arms must be recalibrated relative to one another in context of action, the anatomical properties of the individual limbs also contribute to the recalibration of the action.

The remaining11 experiments showed that the recalibration of an action transferred to actions with a similar *functional* goal (Durgin et al., 2005; Kunz et al., 2013; Rieser et al., 1995; Withagen & Michaels, 2002). For example, Withagen and Michaels (2002) found that walking transferred to crawling which also has the functional goal of locomotion. After walking on a treadmill for 15 minutes in a virtual environment, they found a similar effect of recalibration for both walking and crawling. Since the effect of recalibration was similar for both actions, this indicated a transfer of the recalibration completed for walking into the new task of crawling. Similarly a significant transfer from treadmill walking to side-stepping was found after treadmill walking with a visual disturbance (Rieser et al., 1995, exp. 8). Bingham, Pan, & Mon-Williams (2014, exp.1) found that recalibration transfers between limbs (e.g., from right to the left hand) as limbs are functionally specific to action. The results showed that the distorted feedback transferred from the right to the left hand.

Interestingly, of the 11 experiments that studied functional transfer the 3 experiments mentioned above found a stronger transfer effect while the remaining 8 found a weaker effect of transfer. When analysing these in more detail it seems that the skilfulness of participants in a given task may have been an important factor in the transfer of recalibration. Actions that had similar functional goals, but where participants seemed less skilled, found a no transfer or a weak transfer of recalibration (n=8, Durgin et al., 2005; Kunz et al., 2013; Morton & Bastian, 2004; Rieser et al., 1995). For example, Kunz et al. (2013, exp. 3, 4) found a weak transfer from walking to blind wheel-chairing after participants walked through a virtual hallway for 5-7 minutes (participants were not regular wheelchair users). They also found no transfer of recalibration of wheelchair locomotion to blind-walking after participants wheel-chaired through a virtual hallway. Results also showed that a weak transfer of recalibration from forward walking to sidestepping when the after-effect was measured (Durgin et al., 2005, exp. 5). In addition, Rieser et al. (1995, exp. 9) found that recalibration of turning in place did not transfer to forward walking and vice-versa (Rieser et al., 1995, exp. 10). These experiments all use actions that are not commonly practised and are probably less skilled. It could indicate that a transfer is not possible where skills are not already well-calibrated (i.e., skilful actions imply appropriate calibration).

1. **Discussion**

The aim of this systematic review was to analyse how recalibration can and has been measured and also to evaluate the literature on recalibration. In summary, our results showed that participants recalibrated to disturbances in both perception and action in similar ways. Active exploration was sufficient for fast recalibration only when the relevant information source was available and the skill had been well-learned. When information was restricted this resulted in slower or incomplete recalibration. This is in contrast with Van Andel et al. (2017) who concluded that when the movement itself is explored [re]calibration occurs rapidly. Using a broader article selection, we showed that 1) it is not the movement but instead the perceptual information which needs to be explored in order for recalibration to occur; and 2) recalibration time seems to depend on the magnitude of the disturbance effect and skill rather than simply on exploration.

It is critical that the informational variables that guide a particular action or judgement remain available throughout exploration. For example, sitting quietly after rearrangement does not elicit post-rearrangement (Bruggeman et al., 2005, exp. 4) and informational restriction during rearrangement results in slower or incomplete recalibration (Mark et al. 1990, exp. 3, 4, 5). During recalibration, the perceptual-motor system, which is linked via relevant informational variables, is required to rescale to disturbances in the perceptual or the motor system (Withagen & Michaels, 2004, 2007). This is also shown in Henriques and Cressman's (2012) review, who found that both active or passive exploration resulted in recalibration of hand proprioception (i.e., reaching their hand along a channel versus having the hand passively moved). Importantly, it is often the case that relevant information is made available through action, hence, the broadly accepted conclusion that active exploration is required. Future studies should look closer into active exploration for recalibration. Specifically, they should investigate the availability of information (cf., Bingham & Pagano, 1998) and the duration of exploration. Firstly, the availability of information is important to directly test which informational variables are relied upon during recalibration. This line of research would be best informed by ecological psychology given its strong tradition in attempting to uncover information sources that guide perceptual-motor actions. Secondly, the duration of exploration is important to understand how much active exploration is needed for recalibration and whether this duration is indeed dependent on the skill level and use of appropriate information.

Incomplete recalibration using active exploration was found when the task was not well-learned and calibrated. Participants, who were new to wheelchairs made judgements about the person-plus-wheelchair passibility through apertures (Higuchi et al., 2004; Withagen & Michaels, 2007; Yasuda et al., 2014). The novelty of the wheelchair task might be the reason why participants did not show complete rearrangement over the trials, even if participants were supposedly attuned to (walking) passibility through apertures. A longer period of rearrangement over eight days was more effective in reducing participants’ underestimations after wheelchair-use for four separate days (Higuchi et al., 2004, exp. 2). Results of these experiments indicate that the participants were probably not attuned and calibrated to wheelchair locomotion at the start of the experiment. This is in accordance with results showing that American Football players were better than Rugby players at running through apertures while wearing shoulder pads (Higuchi et al., 2011). Although both groups had extensive experience in judging passibility through apertures, only the American Football players were already calibrated to locomotion wearing shoulder pads. Future studies should ensure that the task is well-learned and calibrated before applying disturbances; in practice this means that studies should always take a baseline measure to ascertain calibration before applying a disturbance.

Results suggest that recalibration is an iterative process, whereby each time the perception-action coupling is used; it updates the informational link between perception and action. There is some evidence to argue that larger disturbances result in longer rearrangement periods (Fernández-Ruiz & Díaz, 1999; Van Hedel & Dietz, 2004). In other words, when the disturbance causes a greater or more obvious error, the rearrangement is slower. For smaller disturbances a couple of trials are sufficient to re-scale the perception-action coupling, while for larger disturbances multiple trials are needed. In addition, Bingham and Romack (1999) found that as participants went through multiple disturbances-rearrangement-removal over several days, the amount of error at disturbance gradually decreased. This would indicate that expert athletes, for example, who may have experienced disturbances to their calibration more often, will take fewer attempts before they are fully recalibrated. More research is necessary to confirm these effects, so research strategies should be carefully employed to tease apart the different stages of recalibration.

This review showed that recalibration is studied using either direct or indirect measures of recalibration and that these measures have been constraining which type of disturbance is used. Direct measures have been used to study both disturbances in perception and action, whereas indirect measures have mainly been used to study disturbances in perception. When analysing the differences between the tasks and the disturbances used in each of these experiments, it was noted that certain disturbances allowed for direct measures while others allowed only for indirect measures of recalibration. On the one hand, experiments using direct measures of recalibration applied a disturbance and measured its direct effect. For example, attaching blocks underneath the feet disturbed action (i.e., error) and allowed for continuous data collection in the rearrangement period to show recalibration (i.e., error reduction). On the other hand, experiments using indirect measures of recalibration applied a disturbance that only shows effects of rearrangement after its removal. For example, when manipulating optic flow using virtual reality, the effects of the optic flow disturbance is only observable upon removal of the optic flow disturbance. These types of disturbances only allow for data collection before and after but not during rearrangement. Since direct measures of recalibration provide a full overview on the recalibration process, future studies are advised to use direct measures with either perception or action disturbances to inform on the trial-by-trial rearrangement process.

The ecological approach was mentioned in the majority of studies reviewed and therefore it is appropriate to discuss how the results relate to this approach both in terms of methods used and results found. In terms of results, some of the studies lend support the ecological approach to visual perception. For example, the most effective way to recalibrate is through active exploration of the perceptual information, as only a few trials of rearrangement were sufficient for (fast) recalibration (Bingham & Romack, 1999; Bruggeman et al., 2005; Mark, 1987; Mark et al., 1990; Saunders & Durgin, 2011; Scott & Gray, 2010). Also, according to the ecological definition of recalibration, actors need to be attuned and well-calibrated (to the appropriate information source) before recalibration can take place. Our results showed that the skilfulness of participants in a given task may be an important factor in both recalibration and its functional transfer (Durgin et al., 2005; Kunz et al., 2013; Morton & Bastian, 2004; Rieser et al., 1995).

In terms of methods, studies using direct measures that capture the trial-by-trial rearrangement period were more informative than those using indirect measures where recalibration was inferred from two discreet moments in time. The emphasis on trial-by-trial changes is in the tradition of the ecological approach as it would not expect the rescaling of perception and action to be accomplished in one error-comparison and error-correction attempt (cf., Desmurget & Grafton, 2000; Henriques & Cressman, 2012). Another methodological point worth mentioning was the use of verbal judgements versus actions as measures of recalibration. An ecological approach would argue against conscious analytical responses because they are far removed from the perceptual-motor task and might ‘recalibrate’ very differently (Heft, 1993; Pagano & Isenhower, 2008). This was what Pagano and Bingham (1998) found when using a very analytical judgement task (i.e., the judgement was done in units of arm length). The remaining 22 articles in this review, which also used judgements, asked participants about reachability or passibility. This type of judgement is much closer to the perceptual-motor task, and hence closer to units of action. Perhaps for this reason our results did not show a pattern of poorer results in judgement studies.

Also consistent with the ecological approach, Bingham and Pagano (1998) state that recalibration is an intrinsic component of perception–action that generates accurate targeted actions. Several of Bingham’s studies suggest that *what* is recalibrated is the mapping between intrinsic units of perception and intrinsic units of action (Bingham et al., 2014; Coats et al., 2014; Pan, Coats, & Bingham, 2014). These studies found that the recalibration of actions was guided by different informational variables. For example, Coats et al. (2014, exp.3) showed that matching target distance was still accurate after participants’ eye-height (EH) was disturbed. The recalibration of matching target distance used inter-pupillary distance (IPD) as an informational variable instead of EH, because the undistorted IPD was considered a more stable informational variable. The concern with uncovering information sources which guide perception-action as well as its recalibration is a central tenet of ecological approach.

***4.1 Conclusions***

Overall, we conclude that active exploration is only sufficient for fast recalibration when the relevant information source is available. Very few trials are sufficient to fully recalibrate provided perceptual information is unrestricted. Recalibration is similar after disturbances to both perception and action. Research lines worth pursuing when studying the mechanisms of recalibration include the study of information sources and skill expertise.

**References**

Bingham, G. P. (2005). Calibration of distance and size does not calibrate shape information: comparison of dynamic monocular and static and dynamic binocular vision. *Ecological Psychology*, *17*(2), 55–74. http://doi.org/10.1207/s15326969eco1702\_1

Bingham, G. P., & Mon-Williams, M. A. (2013). The dynamics of sensorimotor calibration in reaching-to-grasp movements. *Journal of Neurophysiology*, *110*(12), 2857–2862. http://doi.org/10.1152/jn.00112.2013

Bingham, G. P., & Pagano, C. C. (1998). The necessity of a perception–action approach to definite distance perception: Monocular distance perception to guide reaching. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(1), 145–168. http://doi.org/10.1037/0096-1523.24.1.145

Bingham, G. P., Pan, J. S., & Mon-Williams, M. A. (2014). Calibration is both functional and anatomical. *Journal of Experimental Psychology. Human Perception and Performance*, *40*(1), 61–70. http://doi.org/10.1037/a0033458

Bingham, G. P., & Romack, J. L. (1999). The rate of adaptation to displacement prisms remains constant despite acquisition of rapid calibration. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(5), 1331–1346. http://doi.org/10.1037/0096-1523.25.5.1331

Brennan, A. A., Bakdash, J. Z., & Proffitt, D. R. (2012). Treadmill experience mediates the perceptual-motor aftereffect of treadmill walking. *Experimental Brain Research*, *216*(4), 527–534. http://doi.org/10.1007/s00221-011-2956-9

Bruggeman, H., Pick, H. L., & Rieser, J. J. (2005). Learning to throw on a rotating carousel: Recalibration based on limb dynamics and projectile kinematics. *Experimental Brain Research*, *163*(2), 188–197. http://doi.org/10.1007/s00221-004-2163-z

Coats, R. O., Pan, J. S., & Bingham, G. P. (2014). Perturbation of perceptual units reveals dominance hierarchy in cross calibration. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 328–341. http://doi.org/10.1037/a0033802

Crowe, M., & Sheppard, L. (2011). A general critical appraisal tool: An evaluation of construct validity. *International Journal of Nursing Studies*, *48*(12), 1505–1516. http://doi.org/10.1016/j.ijnurstu.2011.06.004

de Oliveira, R. F., Oudejans, R. R. D., & Beek, P. J. (2009). “Experts appear to use angle of elevation information in basketball shooting”: Correction to de Oliveira, Oudejans, and Beek (2009). *Journal of Experimental Psychology. Human Perception and Performance*, *35*(3), 1790. http://doi.org/10.1037/a0018243

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences*, *4*(11), 423–431. http://doi.org/S1364-6613(00)01537-0 [pii]

Dotov, D. G., Frank, T. D., & Turvey, M. T. (2013). Balance affects prism adaptation: Evidence from the latent aftereffect. *Experimental Brain Research*, *231*(4), 425–432. http://doi.org/10.1007/s00221-013-3707-x

Downs, S. H., & Black, N. (1998). The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *Journal of Epidemiology and Community Health*, *52*(6), 377–384. http://doi.org/10.1136/jech.52.6.377

Durgin, F. H., Pelah, A., Fox, L. F., Lewis, J., Kane, R., & Walley, K. a. (2005). Self-motion perception during locomotor recalibration: more than meets the eye. *Journal of Experimental Psychology. Human Perception and Performance*, *31*(3), 398–419. http://doi.org/10.1037/0096-1523.31.3.398

Fernández-Ruiz, J., & Díaz, R. (1999). Prism adaptation and aftereffect: Specifying the properties of a procedural memory system. *Learning & Memory*, *6*(1), 47–53. http://doi.org/10.1101/lm.6.1.47

Fortis, P., Ronchi, R., Calzolari, E., Gallucci, M., & Vallar, G. (2013). Exploring the effects of ecological activities during exposure to optical prisms in healthy individuals. *Frontiers in Human Neuroscience*, *7*(February), 29. http://doi.org/10.3389/fnhum.2013.00029

Franchak, J. M., & Adolph, K. E. (2014). Gut estimates: Pregnant women adapt to changing possibilities for squeezing through doorways. *Attention, Perception {&} Psychophysics*, *76*(2), 460–472. http://doi.org/10.3758/s13414-013-0578-y

Gibson, E. J. (1963). Perceptual learning. *Annu. Rev. Psychol.*, *14*, 29–56.

Gibson, J. J. (1979). *The ecological approach to visual perception*. *Boston: Houghton Mifflin*.

Gibson, J. J., & Gibson, E. J. (1955). Perceptual learning: Differentiation or enrichment? *Psychological Review*, *62*(1), 32–41. http://doi.org/10.1037/h0048826

Hackney, A. L., Cinelli, M. E., & Frank, J. S. (2014). Is the critical point for aperture crossing adapted to the person-plus-object system? *Journal of Motor Behavior*, *46*(5), 319–27. http://doi.org/10.1080/00222895.2014.913002

Heft, H. (1993). A methodological note on overestimates of reaching distance: distinguishing between perceptual and analytical judgements. *Ecological Psychology*, *5*(3), 255–271.

Henriques, D. Y., & Cressman, E. K. (2012). Visuomotor adaptation and proprioceptive recalibration. *J Mot Behav*, *44*(6), 435–444. http://doi.org/10.1080/00222895.2012.659232

Higuchi, T., Murai, G., Kijima, A., Seya, Y., Wagman, J. B., & Imanaka, K. (2011). Athletic experience influences shoulder rotations when running through apertures. *Human Movement Science*, *30*(3), 534–549. http://doi.org/10.1016/j.humov.2010.08.003

Higuchi, T., Takada, H., Matsuura, Y., & Imanaka, K. (2004). Visual estimation of spatial requirements for locomotion in novice wheelchair users. *Journal of Experimental Psychology: Applied*, *10*(1), 55–66. http://doi.org/10.1037/1076-898X.10.1.55

Hirose, N., & Nishio, A. (2001). The process of adaptation to perceiving new action capabilities. *Ecological Psychology*, *13*(1), 49–69. http://doi.org/10.1207/S15326969ECO1301\_3

Jacobs, D. M., & Michaels, C. F. (2006). Lateral interception I: Operative optical variables, attunement, and calibration. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(2), 443–458. http://doi.org/10.1037/0096-1523.32.2.443

Jacobs, D. M., Vaz, D. V., & Michaels, C. F. (2012). The learning of visually guided action: An information-space analysis of pole balancing. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(5), 1215–1227. http://doi.org/10.1037/a0027632

Kunz, B. R., Creem-Regehr, S. H., & Thompson, W. B. (2009). Evidence for motor simulation in imagined locomotion. *Journal of Experimental Psychology. Human Perception and Performance*, *35*(5), 1458–1471. http://doi.org/10.1037/a0015786

Kunz, B. R., Creem-Regehr, S. H., & Thompson, W. B. (2013). Does perceptual-motor calibration generalize across two different forms of locomotion? Investigations of walking and wheelchairs. *PLoS ONE*, *8*(2). http://doi.org/10.1371/journal.pone.0054446

Kunz, B. R., Creem-Regehr, S. H., & Thompson, W. B. (2015). Testing the mechanisms underlying improved distance judgments in virtual environments. *Perception*, *44*(4), 446–453. http://doi.org/10.1068/p7929

Marcilly, R., & Luyat, M. (2008). The role of eye height in judgment of an affordance of passage under a barrier. *Current Psychology Letters Behaviour*, *24*(1). http://doi.org/10.1016/j.neuropsychologia.2011.03.004

Mark, L. S. (1987). Eyeheight-scaled information about affordances: a study of sitting and stair climbing. *Journal of Experimental Psychology. Human Perception and Performance*, *13*(3), 361–370. http://doi.org/10.1037/0096-1523.13.3.361

Mark, L. S., Balliett, J. A., Craver, K. D., Douglas, S. D., & Fox, T. (1990). What an actor must do in order to perceive the affordance for sitting. *Ecological Psychology*, *2*(4), 325–366.

Michaels, C. F., & Carello, C. (1981). *Direction Perception*. *New Jersey: Prentice-Hall, Inc*.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA statement. *Physical Therapy*, *89*(9), 873–880. http://doi.org/10.1371/journal.pmed.1000097

Mohler, B. J., Thompson, W. B., Creem-Regehr, S. H., & Willemsen, P. (2007). Calibration of locomotion resulting from visual motion in a treadmill-based virtual environment. *ACM Transactions on Applied Perception*, *4*(1), 1–15. http://doi.org/10.1145//1227134./1227138

Mon-Williams, M., & Bingham, G. P. (2007). Calibrating reach distance to visual targets. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(3), 645–656. http://doi.org/10.1037/0096-1523.33.3.645

Morton, S. M., & Bastian, A. J. (2004). Prism adaptation during walking generalizes to reaching and requires the cerebellum. *Journal of Neurophysiology*, *92*(4), 2497–2509. http://doi.org/10.1152/jn.00129.2004

Ooi, T. L., Wu, B., & He, Z. J. (2001). Distance determined by the angular declination below the horizon. *Nature*, *414*(6860), 197–200. http://doi.org/10.1038/35102562

Pagano, C. C., & Bingham, G. P. (1998). Comparing measures of monocular distance perception: Verbal and reaching errors are not correlated. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(4), 1037–1051.

Pagano, C. C., & Isenhower, R. W. (2008). Expectation affects verbal judgments but not reaches to visually perceived egocentric distances. *Psychonomic Bulletin & Review*, *15*(2), 437–442. http://doi.org/10.3758/PBR.15.2.437

Pan, J. S., Coats, R. O., & Bingham, G. P. (2014). Calibration is action specific but perturbation of perceptual units is not. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 404–415. http://doi.org/10.1037/a0033795

Redding, G. M., Rossetti, Y., & Wallace, B. (2005). Applications of prism adaptation: A tutorial in theory and method. *Neuroscience and Biobehavioral Reviews*, *29*(3), 431–444. http://doi.org/10.1016/j.neubiorev.2004.12.004

Redding, G. M., & Wallace, B. (1985). Perceptual-motor coordination and adaptation during locomotion: Determinants of prism adaptation in hall exposure. *Perception & Psychophysics*, *38*(4), 320–30. http://doi.org/10.3758/BF03207161

Redding, G. M., & Wallace, B. (1987). Perceptual-motor coordination and prism adaptation during locomotion: A control for head posture contributions. *Perception & Psychophysics*, *42*(3), 269–274. http://doi.org/10.3758/BF03203078

Richter, H., Magnusson, S., Imamura, K., Fredrikson, M., Okura, M., Watanabe, Y., & Långström, B. (2002). Long-term adaptation to prism-induced inversion of the retinal images. *Experimental Brain Research*, *144*(4), 445–457. http://doi.org/10.1007/s00221-002-1097-6

Rieser, J. J., Pick Jr, H. L., Ashmead, D. H., & Garing, A. E. (1995). Calibration of human locomotion and models of perceptual-motor organization. *Journal of Experimental Psychology. Human Perception and Performance*, *21*(3), 480–497. http://doi.org/10.1037/0096-1523.21.3.480

Saunders, J. a, & Durgin, F. H. (2011). Adaptation to conflicting visual and physical heading directions during walking. *Journal of Vision*, *11*(3), 1–10. http://doi.org/10.1167/11.3.15

Scott, S., & Gray, R. (2010). Switching tools: Perceptual-motor recalibration to weight changes. *Experimental Brain Research*, *201*(2), 177–189. http://doi.org/10.1007/s00221-009-2022-z

Stefanucci, J. K., & Geuss, M. N. (2010). Duck!: Scaling the height of a horizontal barrier to body height. *Attention Perception Psychophysics*, *48*(Suppl 2), 1–6. http://doi.org/10.1097/MPG.0b013e3181a15ae8.Screening

Stoffregen, T. A., Yang, C.-M., & Bardy, B. G. (2005). Affordance judgments and nonlocomotor body movement. *Ecological Psychology*, *17*(2), 75–104. http://doi.org/10.1207/s15326969eco1702

Turchet, L., Camponogara, I., & Cesari, P. (2014). Interactive footstep sounds modulate the perceptual-motor aftereffect of treadmill walking. *Experimental Brain Research*, *233*(1), 205–214. http://doi.org/10.1007/s00221-014-4104-9

Uiga, L., Cheng, K. C., Wilson, M. R., Masters, R. S. W., & Capio, C. M. (2015). Acquiring visual information for locomotion by older adults: A systematic review. *Ageing Research Reviews*, *20*, 24–34. http://doi.org/10.1016/j.arr.2014.12.005

Van Andel, S., Cole, M. H., & Pepping, G.-J. (2017). A systematic review on perceptual-motor calibration to changes in action capabilities. *Human Movement Science*, *51*, 59–71. http://doi.org/10.1016/j.humov.2016.11.004

Van Hedel, H. J., & Dietz, V. (2004). Obstacle avoidance during human walking: Effects of biomechanical constraints on performance. *Archives of Physical Medicine and Rehabilitation*, *85*(6), 972–979. http://doi.org/10.1016/j.apmr.2003.07.006

Wagman, J. B., & Abney, D. H. (2012). Transfer of recalibration from audition to touch: Modality independence as a special case of anatomical independence. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 589–602. http://doi.org/10.1016/j.bbr.2008.09.018

Waller, D., & Richardson, A. R. (2008). Correcting distance estimates by interacting with immersive virtual environments: Effects of task and available sensory information. *Journal of Experimental Psychology-Applied*, *14*(1), 61–72. http://doi.org/10.1037/1076-898X.14.1.61

Withagen, R., & Michaels, C. F. (2002). The calibration of walking transfers to crawling: Are action systems calibrated? *Ecological Psychology*, *14*(4), 223–234. http://doi.org/10.1207/S15326969ECO1404{\_}2

Withagen, R., & Michaels, C. F. (2004). Transfer of calibration in length perception by dynamic touch. *Percept Psychophys*, *66*(8), 1282–1292.

Withagen, R., & Michaels, C. F. (2007). Transfer of calibration between length and sweet-Spot perception by dynamic touch. *Ecological Psychology*, *19*(1), 1–19. http://doi.org/10.1080/10407410709336948

Yasuda, M., Wagman, J. B., & Higuchi, T. (2014). Can perception of aperture passability be improved immediately after practice in actual passage? Dissociation between walking and wheelchair use. *Experimental Brain Research*, *232*(3), 753–764. http://doi.org/10.1007/s00221-013-3785-9

Yu, Y., Bardy, B. G., & Stoffregen, T. A. (2011). Influences of head and torso movement before and during affordance perception. *Journal of Motor Behavior*, *43*(1), 45–54. http://doi.org/10.1080/00222895.2010.533213

Yu, Y., & Stoffregen, T. A. (2012). Postural and locomotor contributions to affordance perception. *Journal of Motor Behavior*, *44*(5), 305–311. http://doi.org/10.1080/00222895.2012.706659