Human Movement Science 56 (2017) 54–70

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Full Length Article

Recalibration in functional perceptual-motor tasks: A systematic review

Milou Tessa Brand*, 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

ARTICLE INFO

Keywords:
Recalibration
Scaling
Perception
Action
Ecological psychology

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.

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 (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

* Corresponding author.
E-mail address: m.brand@lsbu.ac.uk (M.T. Brand).

http://dx.doi.org/10.1016/j.humov.2017.10.020
Received 12 July 2017; Received in revised form 27 October 2017; Accepted 28 October 2017

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 the only review on [re]calibration by Van Andel, Cole, and Pepping (2017). Calibration and recalibration may have been used interchangeably, because they are thought to be similar processes of scaling information to perception and action. However, the distinction is important, because they differ in terms of: a) what may elicit these processes; b) how long they may take to complete the process; 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.

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 Fig. 1 as an illustration of the recalibration process (extended from Redding et al. (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

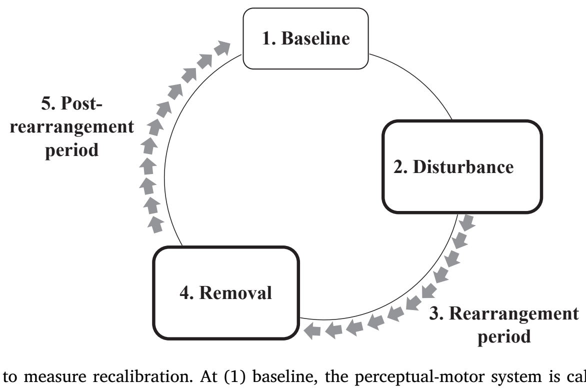

Fig. 1. Schematic illustration of strategies to measure recalibration. At (1) baseline, the perceptual-motor system is calibrated; (2) represents a disturbance to the perceptual-motor system; (3) in the rearrangement period each of the Gray arrows represents a trial or measurement of recalibration; (4) represents the removal of the disturbance and (5) in the post-rearrangement period each of the Gray arrows represents a trial or measurement of recalibration. Direct measures of recalibration include measures at (2) and (3) capturing both the disturbance and the rearrangement period. On the other hand, indirect measures of recalibration include measures at (1) and (4) capturing the baseline and the effects upon removal of the disturbance.

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 re-arrangement 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, 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.

2. 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 Fig. 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.

Fig. 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.

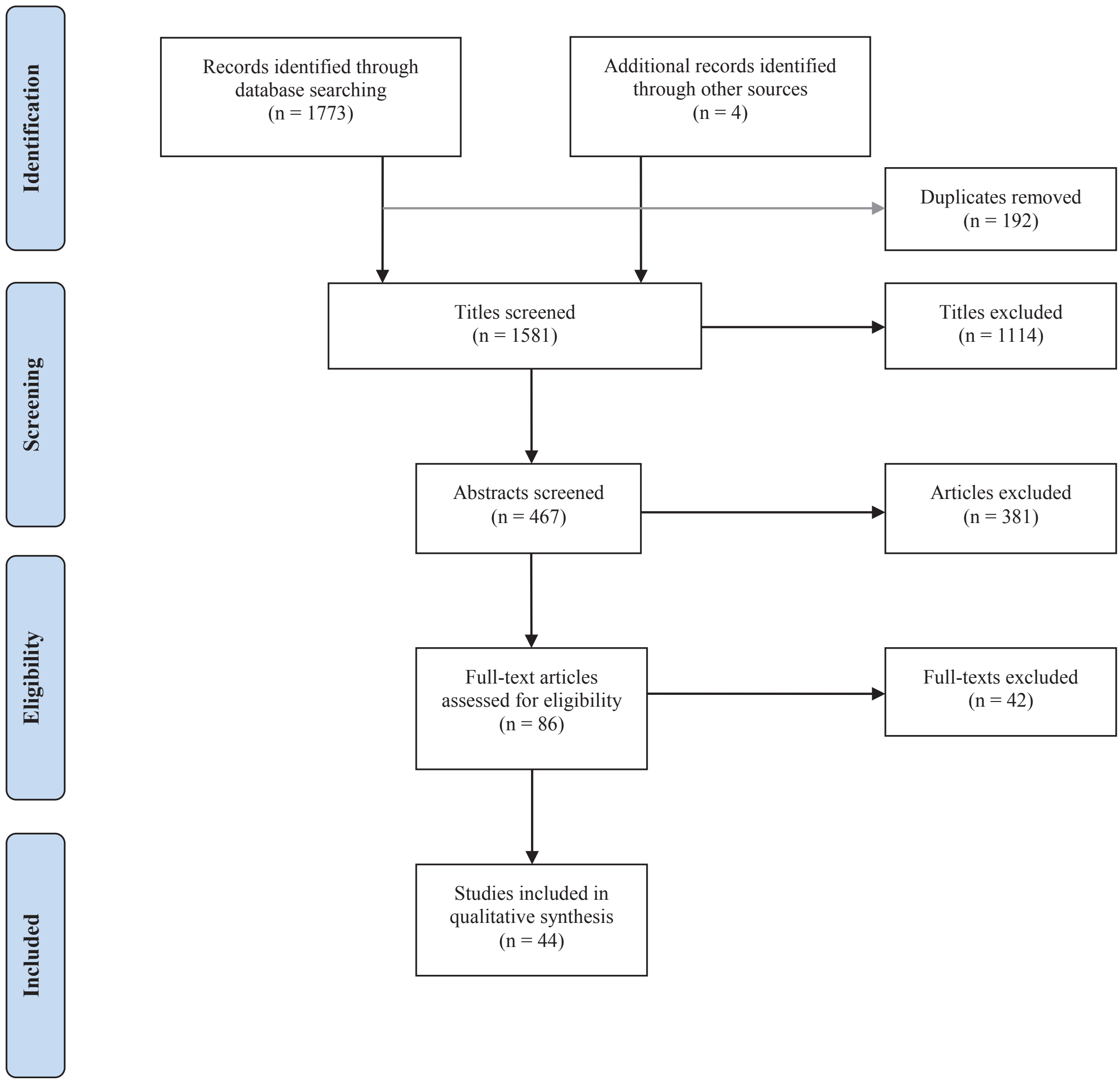

Fig. 2. PRISMA flowchart of literature search results. From top to bottom the flowchart shows identification of 1777 articles, the screening of 1581 titles and 467 abstracts, the further screening for eligibility of 86 full-text articles, and the inclusion of 44 articles.

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.

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.

Table 1
Quality assessment items and their origin. Experiments were assessed on a scale of 0–2.

	Quality assessment items	Origin
1	Is the hypothesis, aims, objectives clearly described?	Downs and Black (1998); CCAT*
2	Is the design clearly described?	CCAT
3	Is the procedure of the experiment clearly described?	Downs and Black (1998); CCAT
4	Are the tasks clearly defined?	Downs and Black (1998)
5	Are the data collection methods clearly described?	CCAT
6	Was the data processing clearly defined?	Uiga et al. (2015)
7	Were the outcome measures clearly defined?	Downs and Black (1998); CCAT
8	Are the main findings of study clearly described?	Downs and Black (1998); CCAT
9	Does study provide estimates of random variability in the data?	Downs and Black (1998)
10	Were participants representative of population under study?	Downs and Black (1998); CCAT
11	Are the characteristics of participants clearly described?	Downs and Black (1998); CCAT
12	Was there a control group?	Uiga et al. (2015)

* CCAT by Crowe and Sheppard, 2011.

3. 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 et al., 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; Kunz, Creem-Regehr, & Thompson, 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 et al. (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 s of treadmill blind-running (Durgin et al., 2005, exp. 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

Table 2
Quality assessment scores of the included experiments.

Included experiments	Items												
	1	2	3	4	5	6	7	8	9	10	11	12	Total
Bingham (2005)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Bingham and Mon-Williams (2013)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Bingham and Pagano (1998 – exp. 1)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Bingham and Pagano (1998 – exp. 2)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Bingham and Pagano (1998 – exp. 3)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Bingham and Pagano (1998 – exp. 4)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Bingham and Romack (1999)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Bingham et al. (2014 – exp. 1)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Bingham et al. (2014 – exp. 2)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Brennan et al. (2012)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Bruggeman et al. (2005 – exp. 1)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Bruggeman et al. (2005 – exp. 3)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Bruggeman et al. (2005 – exp. 4)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Coats et al. (2014, exp. 1)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Coats et al. (2014, exp. 2)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Coats et al. (2014, exp. 3)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Dotov et al. (2013)	2	1	2	2	2	2	2	2	2	0	2	2	88%
Durgin et al. (2005 – exp. 2)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Durgin et al. (2005 – exp. 3)	2	2	2	2	2	1	2	2	0	0	1	0	67%
Durgin et al. (2005, exp. 1)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Durgin et al. (2005, exp. 5)	2	2	2	2	2	1	2	2	2	0	1	0	75%
Durgin et al. (2005, exp. 6)	2	2	2	1	0	0	0	2	1	0	1	0	46%
Fernández-Ruiz and Díaz (1999 – exp. 1)	0	2	2	2	1	2	2	1	0	0	0	0	50%
Fernández-Ruiz and Díaz (1999 – exp. 2)	0	2	2	2	1	2	2	1	0	0	0	0	50%
Fernández-Ruiz and Díaz (1999 – exp. 3)	0	2	2	2	1	2	2	1	0	0	0	0	50%
Fortis et al. (2013)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Franchak and Adolph, 2014 – exp. 3	2	2	2	2	2	2	2	2	2	0	2	0	83%
Hackney et al. (2014)	2	2	2	2	2	2	2	2	1	0	2	0	79%
Higuchi et al. (2004) – exp. 1	2	2	2	2	2	2	2	2	0	0	2	2	83%
Higuchi et al. (2004) – exp. 2	2	2	2	2	2	2	2	2	0	0	2	2	83%
Hirose and Nishio (2001)	2	2	2	2	2	2	2	2	1	0	2	0	79%
Kunz et al. (2009 – exp. 5)	2	2	2	2	2	2	2	2	1	0	2	0	79%
Kunz et al. (2013 – exp. 1)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Kunz et al. (2013 – exp. 2)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Kunz et al. (2013 – exp. 3)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Kunz et al. (2013 – exp. 4))	2	2	2	2	2	2	2	2	2	0	0	0	75%
Kunz et al. (2015)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Marcilly and Luyat (2008)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Mark (1987 – exp. 2)	2	2	2	2	2	2	2	2	1	0	2	0	79%
Mark (1987 – exp. 3)	2	0	2	2	2	2	2	2	0	0	0	0	58%
Mark et al., 1990 – exp. 1	2	2	2	2	2	2	2	2	0	0	0	0	67%
Mark et al., 1990 – exp. 2	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mark et al., 1990 – exp. 3	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mark et al., 1990 – exp. 4	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mark et al., 1990 – exp. 5	2	2	2	2	2	2	2	2	2	0	0	0	75%
Mark et al., 1990 – exp. 6	2	2	2	2	2	2	2	2	2	0	0	0	75%
Mohler et qal. (2007 – exp.1)	2	2	2	2	0	0	0	2	2	0	0	0	50%
Mohler et qal. (2007 – exp. 2)	2	2	2	2	0	0	0	2	1	0	0	0	46%
Mon-Williams and Bingham (2007 – exp.1)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mon-Williams and Bingham (2007 – exp. 2)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mon-Williams and Bingham (2007 – exp. 3)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mon-Williams and Bingham (2007 – exp. 4)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Morton and Bastian (2004)	2	2	2	2	2	2	2	1	0	0	2	0	71%
Pagano and Bingham (1998)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Pan et al. (2014 – exp. 3)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Redding and Wallace (1985 – exp.1)	2	2	2	2	2	2	2	1	0	0	0	0	63%
Redding and Wallace (1985 – exp. 2)	2	2	2	2	2	2	2	1	0	0	0	0	63%
Redding and Wallace (1985 – exp. 3)	2	2	2	2	2	2	2	1	0	0	0	0	63%
Redding and Wallace (1987)	2	1	2	2	2	2	2	1	0	0	0	0	58%
Richter et al. (2002)	2	2	2	2	1	2	1	2	1	0	2	2	79%
Rieser et al. (1995 – exp. 1)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Rieser et al. (1995 – exp. 10)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 – exp. 2)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 – exp. 3)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 – exp. 4)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 – exp. 5)	2	2	2	2	2	2	2	2	2	0	0	0	75%

(*continued on next page*)

Table 2 (*continued*)

Included experiments	Items												
	1	2	3	4	5	6	7	8	9	10	11	12	Total
Rieser et al. (1995 – exp. 6)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 – exp. 7)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 – exp. 8)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 – exp. 9)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Saunders and Durgin (2011)	2	0	2	2	2	0	0	2	1	0	1	0	50%
Scott and Gray (2010 – exp. 1)	2	2	2	2	2	2	2	2	1	0	2	2	88%
Scott and Gray (2010 – exp. 2)	2	2	2	2	2	2	2	2	1	0	2	2	88%
Stefanucci and Geuss (2010 – exp. 3)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Stefanucci and Geuss (2010 – exp. 4)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Stefanucci and Geuss (2010 – exp. 4b)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Stoffregen et al. (2005 – exp.1)	2	0	2	2	2	0	0	2	1	0	1	0	50%
Stoffregen et al. (2005 – exp. 2)	2	0	2	2	2	0	0	2	2	0	1	0	54%
Turchet et al. (2014)	2	2	2	2	2	2	2	2	1	0	2	0	79%
van Hedel and Dietz (2004)	2	0	2	2	2	2	2	2	2	0	1	0	71%
Wagman and Abney (2012 – exp. 3)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Waller and Richardson (2008 – exp. 1)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Waller and Richardson (2008 – exp. 2)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Waller and Richardson (2008 – exp. 3)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Withagen and Michaels (2002)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Withagen and Michaels (2007 – exp. 1)	2	2	2	2	2	2	1	2	1	0	1	0	71%
Withagen and Michaels (2007 – exp. 2)	2	2	2	2	2	2	1	2	1	0	1	0	71%
Yasuda et al., 2014 – exp. 1	2	2	2	2	2	2	2	2	2	0	2	2	92%
Yasuda et al., 2014 – exp. 2	2	2	2	2	2	2	2	2	2	0	2	2	92%
Yu and Stoffregen (2012)	2	2	2	2	2	2	2	2	0	0	2	2	83%
Yu et al. (2011)	2	2	2	2	2	2	2	2	1	0	2	2	88%

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 analyse 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 (5–12 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

Table 3
Quality of the rearrangement period. Experiments 1–7 showed rearrangement after a small amount of trials with active exploration, experiments 8–12 showed rearrangement after a fixed amount of trials with active exploration, experiments 13–17 showed incomplete recalibration using active exploration due to restricted availability of information, experiments 18–21 showed incomplete recalibration using active exploration due to a lack of experience, and experiments 22–30 restricted exploration.

No.	Author (year)	Participants	Task	Disturbance to baseline calibration	Activity and duration of rearrangement period	Amount of trials needed for recalibration
1	Bingham and Romack (1999)	5 total, 2 female and 3 male (18–28 yrs)	Participants reached from launch platform next to the participant to place a stylus in a target hole in front (varied: continued until participant reached the criterion within a max. of 4 blocks)	10 degree displacement prism glasses	Reaching to place a stylus in a target hole in front with alternating clear goggles and 10 degree displacement goggles	The number of trials per block decreased over 3 days: 10.2 trials on day 1, 5.2 on day 2, and 5.6 on day 3. The rate of decrease was the same each day (0.30 trials per block)
2	Bruggeman et al. (2005 – exp. 4)	12 right-handed undergraduate students (20 ± 4 yr.)	Participants made underhand throws to targets (12 blocks of 5 throws)	Throws on a rotating beam to hit the target on the other end of the beam	Made underhand throws for 60 throws	75 % of the beanbags landed on the platform within 10 throws
3	Mark (1987, exp.2)	12 female undergraduate students	Participants judged their maximum climbable riser height or maximum seat height (6 blocks of height-judgments)	10-cm high blocks underneath their feet	Walked around after each block of judgment series	6 judgement trials
4	Mark et al. (1990, exp. 1)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum sitting height (12 blocks of height-judgments)	10-cm high blocks underneath their feet	Walked around after each block of judgment series	6 judgement trials
5	Saunders and Durgin (2011)	12 undergraduate students	Participants walked to a visible target on the ground (20 trials)	Participants were showed environments that either provided target-motion or ground-flow motion with a 10 degrees offset	Walked to a target for 20 trials	Within 10 trials mean heading errors decreased
6	Scott and Gray (2010, exp. 1)	30 total, 19 male and 11 female (23.4 ± 0.8 yr.)	Participants swung a baseball bat at a simulated approaching baseball	Lighter or heavier bat weight	Made baseball swings for 2 training blocks of 15 trials	Lighter group within 5 pitches; Heavier group within 10 pitches

(continued on next page)

Table 3 (*continued*)

No.	Author (year)	Participants	Task	Disturbance to baseline calibration	Activity and duration of rearrangement period	Amount of trials needed for recalibration
7	Scott and Gray (2010, exp. 2)	20 total, 14 male and 6 female (24.1 ± 0.6 yr.)	Participants swung a baseball bat at a simulated approaching baseball	Heavier bat weight	Made baseball swings for 2 training blocks of 15 trials	Within 15 pitches
8	Fortis et al. (2013)	48 total - young group: 24 total (24 ± 2.67 yrs), old group: 24 total (68 ± 5.74 yrs)	Participants pointed movements to a target	Prisms displacing the visual field 10 degrees horizontally to the right	Pointing movements to a target	90 pointing movements
9	Franchak and Adolph (2014, exp.3)	12 total (18–22 yr., M = 20.6 yr.)	Participants made judgements whether they would fit through doorways (30 judgements)	Wearing a pregnancy pack	Walked through apertures for 20 walking trials	20 practice trials
10	Hackney et al. (2014)	22 total, 13 women and 9 men (22.8 ± 1.5 yr.)	Participants walked at a natural pace toward the goal and avoid colliding with the two obstacles (4 tray size blocks: 3 trials × 4 apertures widths)	No-tray (always first block) vs. tray (1.2, 1.4 and 1.6 times shoulder-width)	Walked while avoiding obstacles for 36 judgements	3 blocks of 12 trials
11	Richter et al. (2002)	14 total - experimental group (7 male: (25 ± 2.3 yr.) and control group (7 male: 27 ± 4.9 yr.)	Participants threw arrows at a dartboard, or ambulated forward or sideways through a narrow obstacle course	Binocular prism glasses inverted visual field (180 degrees)	Played darts, or ambulated forward, or sideways through obstacle course for 7 days	All tasks improved over the 7 days
12	van Hedel and Dietz (2004)	18 young volunteers	Participants walked on a treadmill, with reduced vision and auditory feedback, and stepped over a randomly approaching obstacle	An AFO (ankle–foot), KO (knee) or KAFO (ankle and knee) orthosis attached to their left leg	Walked on a treadmill for 50 steps	AFO within 50 trials, but KO and KAFO need a longer rearrangement for similar recalibration
13	Bingham and Pagano	4 total, 1 female and 3 male (29–39 yrs)	Participants reached from	A verbal judgement, headcam reach, static-camera reach,	Reaching to place a stylus in a target	Moving headcam, headcam-ballistic:

(*continued on next page*)

Table 3 (*continued*)

No.	Author (year)	Participants	Task	Disturbance to baseline calibration	Activity and duration of rearrangement period	Amount of trials needed for recalibration
	(1998 – exp.1)		launch platform next to participant to place a stylus in a target hole	headcam-ballistic reach, restricted-field monocular reach or monocular reach	hole (25 trials each)	no ability for recalibration. Some participants slightly recalibrated in restricted-field viewing.
14	Bingham and Pagano (1998 – exp.2)	8 total, 3 female and 5 male (18–39 yrs)	Participants reached from launch platform next to participant to place a stylus in a target hole	A restricted field or monocular viewing	Reaching to place a stylus in a target hole (25 trials each)	The restricted-field viewing: recalibration using feedback from reaching. Monocular: no recalibration.
15	Bingham and Pagano (1998 – exp. 3)	2 total	Participants reached to place a stylus under a target surface to align the stylus	Headcam or monocular viewing	Reaching to align a stylus in a target surface (25 trials each)	Headcam and monocular viewing: no recalibration
16	Bingham and Pagano (1998 – exp. 4)	4 total, 2 female and 2 male (18–21 yrs)	Participants reached from launch platform next to participant to place a stylus in a target hole	Monocular or binocular viewing	Reaching to place a stylus in a target hole (25 trials each)	Binocular: more accurate than monocular viewing (no recalibration)
17	Bingham (2005)	22 total, 8 female and 14 men, 19–30 yrs. 9 monocular, 6 binocular and 7 dynamic binocular group	Participants reached to touch the front, back and sides of a virtual target with a hand-held stylus	Monocular viewing restriction and dynamic conditions (participant first moved head and torso while counter-rotating the head)	Participants reached to touch a virtual target (5 blocks of 20 trials)	Performance was better when using binocular vision
18	Yasuda et al. (2014) , exp. 1	49 total, 27 female and 22 male (23.6 ± 5 yr.)	Participants reported whether apertures of various widths were passable (6 trials)	Holding a 69-cm horizontal bar (not allowed to turn shoulders)	Walked through apertures holding a horizontal bar for 21 trials	21 practice trials
19	Higuchi et al. (2004, exp. 1)	12 male college students (23 ± 4.2 yr.)	Participants estimated whether they could pass through the aperture without rotating	Sitting in a wheelchair (free to move the head, body and arms but had to remain seated)	Rolled their wheelchair through apertures for 20–28 rearrangement trials	No differences pre- and post-practice

(continued on next page)

Table 3 (*continued*)

No.	Author (year)	Participants	Task	Disturbance to baseline calibration	Activity and duration of rearrangement period	Amount of trials needed for recalibration
			shoulders and touching it.			
20	Higuchi et al. (2004, exp. 2)	8 male college students (23.6 ± 3.7 yr.)	Participants estimated whether they could pass through the aperture without rotating shoulders and touching it	Sitting in a wheelchair - free to move the head, body and arms but had to remain seated.	Rolled their wheelchair through apertures. They performed 3 blocks of 5 trials with different widths for 8-days within 4 weeks.	Slight improvement over the practice sessions, but the perceptual boundary was still less than 1.0 in the 8 th day session
21	Yasuda et al. (2014) , exp. 2	37 total, 19 female and 18 male (22.8 ± 5.9 years)	Participants reported whether apertures of various widths were passable	Sitting in a wheelchair	Rolled their wheelchair through apertures for 21 trials	No improvement of perception of passibility after the practice
22	Mark (1987, exp.3)	8 female undergraduate students	Participants judged their maximum climbable riser height or maximum seat height	10-cm high blocks underneath their feet (body sway only)	Usage of body sway for 12 judgement trials	9 judgement trials
23	Mark et al. (1990, exp. 2)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (body sway only)	Usage of body sway for 12 judgement trials	12 judgement trials
24	Mark et al. (1990, exp. 3)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (while looking through a monocular peephole)	Usage of limited body sway for 12 judgement trials	No recalibration
25	Mark et al. (1990, exp. 4)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (in an awkward stance position)	Usage of limited body sway for 12 judgement trials	No recalibration
26	Mark et al. (1990, exp. 5)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (without any body sway)	Made judgements for 12 trials	No recalibration (only a few observers improved their judgements)
27	Mark et al. (1990, exp. 6)	24 total, 12 female and 12 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (restriction as in experiment normal stance or peephole condition)	Practiced sitting on the apparatus 2-3x before the perceptual task for 12 judgement trials	No recalibration
28		12 undergraduate students, 5 men and 7 women (18–35 years)				12 judgement trials

(*continued on next page*)

Table 3 (*continued*)

No.	Author (year)	Participants	Task	Disturbance to baseline calibration	Activity and duration of rearrangement period	Amount of trials needed for recalibration
	Stoffregen et al. (2005, exp. 1)		Participants made judgments of their own maximum seat height	10-cm high blocks underneath their feet (body sway only)	Usage of body sway for 12 judgement trials	
29	Yu and Stoffregen (2012)	48 total, 20 men and 28 women (18–52 years)	Participants judged the lowest lintel under which they could roll in the wheelchair	Sitting in a wheelchair (active or passive movement & unrestrained or restrained head movement).	Rolled a wheelchair up and down a 25 m hallway for 2 min	The accuracy of the judgments improved only for actively controlled wheelchair locomotion (head restrained or non-restrained)
30	Yu et al. (2011)	48 total, 18 men and 30 women (18–32 years)	Participants judged the lowest lintel under which they could roll in the wheelchair	Sitting in a wheelchair (with restrained or unrestrained head movement during practice and/or judgments)	Rolled a wheelchair up and down a 25 m hallway for 2 min	Judgments were more accurate when head movement was unrestrained rather than restrained

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.

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)

3.6. Transfer of recalibration

In total, 12 experiments studied whether the transfer of recalibration is functional, anatomical or both. In their experiment Bingham et al. (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 remaining 11 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 min 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 et al. (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 min (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).

4. 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.

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.

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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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. *Journal of Experimental Psychology. Human Perception and Performance, 35*(3), 1790. http://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.doi.org/10.3758/s13414-013-0578-y.

Gibson, E. J. (1963). Perceptual learning. *Annual Review of Psychology, 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://dx.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), 319–327. http://dx.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. *Journal of Motor Behavior, 44*(6), 435–444. http://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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), 320–330. http://dx.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://dx.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://dx.doi.org/10.1007/s00221-002-1097-6.
Rieser, J. J., Pick, H. L., Jr, 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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.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://dx.doi.org/10.1207/S15326969ECO1404{_}2.
Withagen, R., & Michaels, C. F. (2004). Transfer of calibration in length perception by dynamic touch. *Perception & Psychophysics, 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://dx.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://dx.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://dx.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://dx.doi.org/10.1080/00222895.2012.706659.