A Systematic Review on Perceptual-Motor Calibration to Changes in Action Capabilities

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Abstract

Perceptual-motor calibration has been described as a mapping between perception and action, which is relevant to distinguish possible from impossible opportunities for action. To avoid movement errors, it is relevant to rapidly calibrate to immediate changes in capabilities and therefore this study sought to explain in what conditions calibration is most efficient. A systematic search of seven databases was conducted to identify literature concerning changes in calibration in response to changes in action capabilities. Twenty-three papers satisfied the inclusion criteria. Data revealed that calibration occurs rapidly if there is a good match between the task that requires calibration and the sources of perceptual-motor information available for exploration (e.g. when exploring maximal braking capabilities by experiencing braking). Calibration can take more time when the perceptual-motor information that is available is less relevant. The current study identified a number of limitations in the field of perceptual-motor research. Most notably, the mean participant age in the included studies was between 18 and 33 years of age, limiting the generalizability of the results to other age groups. Also, due to inconsistent terminology used in the field of perceptual-motor research, we argue that investigating calibration in older cohorts should be a focus of future research because of the possible implications of impaired calibration in an ageing society.

Keywords: Sensory Perception; Motor Processes; Perception–action coupling; Perceptual-Motor Calibration

1. Introduction

The framework of direct perception suggests that movement is guided by one's perception of *affordances*; that is, the opportunities for action within an individual's environment (Gibson 1979; Stoffregen 2003). Perception of affordances logically requires scaling to action capabilities to allow distinction between the possible and impossible opportunities for action in an individual's surroundings. This scaling is known as *(perceptual-motor) calibration* (Bingham & Pagano, 1998; Warren, 1984; Withagen & Michaels, 2007).

Calibration has generally been observed in research considering the perception of affordances in a certain environment. In an experiment aimed at analyzing stair climbing behavior as a dynamical system, Warren (1984) was one of the first to study perception of affordances. In his seminal study, Warren (1984) assessed individuals' capacities to accurately perceive maximal and optimal climbable stair heights, given their own action capabilities. The results showed that, independent of their height, all participants perceived steps of 0.88 times their leg length to be their maximal climbable stair height. Furthermore, independent of the participant's height, a step that stood 0.26 times the participant's leg length in height was perceived to be the optimal stair height. These findings demonstrated that all participants used a scaling of their body size (in this case leg length) for perception of possibilities for action (in this case stair climbing), indicating that these participants were calibrated to their body size (given that body size is related to their action capabilities). Following the early work of Warren (1984), numerous other studies have focused on the perception of affordances and their scaling with action capabilities in different types of action (see Barsingerhorn, Zaal, Smith, & Pepping, 2012; for a historical overview).

Interested in the mechanisms of calibration, Bingham and colleagues (Bingham & Pagano, 1998; Bingham, Pan, & Mon-Williams, 2014; Coats, Pan, & Bingham, 2014) introduced the ‘mapping’ theory of calibration, which states that embodied units of perception are matched with embodied units of action. According to this theory, human motor control is governed by one’s perception of the environment in terms of their own perception-action system. Calibration can be perturbed following a change of sensory units (e.g. changing the meaning of sensory information) and following action unit changes (e.g. manipulating stride length by adding weights to the body). Both types of manipulation have been considered by previous research.

Sensory units can be manipulated by disturbances of perceptual information. This has been extensively studied by experimentally manipulating information using a prism adaption paradigm (Bingham & Romack, 1999; Redding & Wallace, 1997). In general, these studies show that with practice and feedback, humans are able to adapt (*recalibrate*) to the new mapping. Fernández-Ruiz, Hall, Vergara and Díaz (2000) studied adaptation to vision shifted by prisms and reported differences in learning rates between younger and older adults. Their older group of participants needed more practice before they completely recalibrated to the new mapping. Whilst these studies do give an interesting insight into the mechanisms of calibration, it is important to note that such a manipulation is unlikely to occur in real life. Arguably, one of the few occurrences of changing the mapping in real life would be when a person starts to wear (multifocal-) glasses, but in this situation, the effects will be smaller compared to the experimental conditions (a person wears glasses with the aim of improving vision, not in order to challenge motor control).

The second way in which calibration can be perturbed is by a change in action capabilities. Changes in action capabilities occur naturally throughout the lifespan, such that as we mature from childhood to adulthood, we develop improved action capabilities and as we age, our capabilities decrease. In addition to these natural changes in action capabilities, one’s capabilities can change more rapidly due to biological processes, such as the fatigue experienced by an athlete during a sports match that can decrease strength or running ability. Furthermore, action capabilities can be altered directly, by restrictions imposed by clothing or footwear. For instance, a person could put on shoes with high heels, which will directly influence step size. Considering that these changes could occur at any time, it could be argued that this would be the type of calibration that is predominantly required in everyday motor control.

Considering changes in action capabilities, decreases in capabilities seem to be especially relevant, since these decreases have been linked to the occurrence of falls in an older age bracket (Luyat, Domino, & Noël, 2008). Luyat et al. (2008) hypothesized that the higher incidence of falls in older adults could be the result of misperception of affordances, instigated by not adequately calibrating to the declines in physical function that are associated with aging. Plumert (1995) previously reported a link between decreased accuracy in the perception of action capabilities and a history of accidental injuries in children. Combined, these studies suggest that the falls experienced by older adults may be explained, at least in part, by an impaired capacity for these individuals to calibrate to the age-related changes in their action capabilities.

With the potential relevance of calibration for prevention age related accidents, such as of falls, it is of particular interest to consider what is required for an individual to calibrate to their capabilities. An improved understanding of this process may be of relevance to better understanding the mechanism(s) of age related accidents, as it is well known that their action capabilities decline with age, but it is currently unclear what is required for these individuals to recalibrate to age-related changes in action capabilities.

1.1 The current study

Collectively, the existing literature suggests that one's capacity to safely navigate their environment depends upon their ability to calibrate to changes in their action capabilities. Given this understanding, the current study focusses on the process of calibration to changes in action capabilities. Previous studies have reported that the process of calibration in general is highly dependent on exploration of the perception-action mapping (Adolph, Eppler, Marin, Weise, & Wechsler Clearfield, 2000; Barsingerhorn et al., 2012; Stoffregen, Yang, Giveans, Flanagan, & Bardy, 2009; Yu & Stoffregen, 2012) or feedback on performed movements (Bingham & Pagano, 1998; Withagen & Michaels, 2005).Yet individually, these theoretical studies do not consider practical issues, such as: the amount of exploration allowed; the amount of experience that is required for effective calibration; or the existence of individual differences in this process. The current study aimed to synthesize the existing literature on perceptual-motor calibration to changes in action capabilities with a focus on understanding the effectiveness of calibration.

2. Methods

2.1 Methods for literature search

A series of systematic searches were performed in seven academic databases: PubMed, EMBASE, Cochrane Library, CINAHL, PsycInfo, SPORTdiscus and Web of Science. These searches placed no restrictions on the publication date of the papers and aimed to identify all relevant literature concerned with perceptual-motor calibration. Each search was structured to include three collections of terms; the first relating to calibration; the second relating to perception; and the third relating to action. The terms included within each of these collections were separated with the operator ‘OR’, while the three collections of terms were linked with the operator ‘AND’.

To be eligible for inclusion in this systematic review, papers were required to: i) be written in Dutch or English; ii) be an original full-length paper (i.e. not a review or conference paper); iii) be peer-reviewed; iv) focus on otherwise healthy individuals (i.e. not a patient group); and v) include a measure of perceptual-motor calibration to a change in action capabilities as the main outcome. To clarify, this means that some papers might include a manipulation of action capabilities but still could be excluded because the focus was not on the calibration or adaptation process. Of the total search results, duplicates were removed and articles were screened based on title and the criteria stated above. After title selection, articles were screened based on the abstract and full text for the same criteria. The resulting papers were supplemented by an analysis of the references that were cited in the reference lists of the included papers and by citation tracking. These additional papers were selected on title and also underwent a screening on abstract and full text, similar to the articles included from the database search. The full details of the search strategy have been provided as Appendix A.

2.2 Paper review process

The titles and abstracts of all papers retrieved via the systematic search strategy were independently screened by the authors (SvA, GJP, MHC) based on the outlined inclusion criteria. Any discrepancies in the reviewers’ decisions to include or exclude a paper were discussed until a consensus was reached. The full-text of the papers that appeared to meet the inclusion criteria based on their title and/or abstract were reviewed and all papers that were deemed to meet all of the inclusion criteria were included in the systematic review. For each of these papers, details concerning the study’s reference, target population (e.g. age characteristics), response type, primary outcome measures and mechanisms of calibration (if available) were extracted and synthesized.

2.3 Quality assessment

Quality assessment of studies was performed with the Crowe Critical Appraisal Tool (CCAT; Crowe, Sheppard, & Campbell, 2012; Crowe & Sheppard, 2011). The CCAT checklist was developed to facilitate the assessment of the methodological quality of a variety of different study designs, including cross-sectional studies. Given the outlined inclusion criteria and the specific scope of this review, the majority of the included studies were expected to be cross-sectional in nature, hence the CCAT was considered to be a suitable instrument for assessing their methodological quality. The CCAT consists of 8 sub-scales that each evaluates a different aspect of the research article. By summing the items within each of these sub-scales, it is possible to identify specific strengths and shortcomings in the methodological reporting of the papers. The scores for the eight sub-scales are then summed and expressed as a percentage to provide an overall measure of the methodological quality of each paper. As the CCAT protocol does not provide a specific method for interpreting the percentage scores, the range of possible scores was divided into quintiles, with papers assessed as being of either; i) very low (0-20%); ii) low (21-40%); iii) moderate (41-60%); iv) high (61-80%); or v) very high (81-100%) methodological quality.

3. Results

3.1 Selection process

The systematic search of the seven databases resulted in a total of 2054 potential papers being identified. Of these papers, 714 were removed as duplicates and 248 were excluded as they were either written in a language other than English or Dutch (n=27) or they were not considered to be an original full-length research article (n=221). The titles and abstracts of the remaining 1092 papers were independently screened by three reviewers, resulting in the exclusion of a further 874 papers based on title and 202 papers based on abstract. Citation tracking and screening of the reference lists of the remaining 16 studies resulted in the identification of 10 additional papers that were considered potentially relevant for the review. Following full-text review of these 26 studies, three studies were considered ineligible: based on the abstract these studies appeared to consider changes in action capabilities, but analysis of the full text did not indicate a specific manipulation of action capabilities, resulting in a total of 23 studies being included in this review (Figure 1).

3.2 Quality assessment

On the basis of the CCAT, the methodological quality of the included papers ranged from 58% to 85%, with a mean score of 72%. Three papers (13%) scored a moderate methodological quality, 17 (78%) papers scored high methodological quality and three papers (9%) scored very high methodological quality (Table provided in appendix B). Many of the papers included in this review scored similarly high for the categories evaluating preliminaries, introduction, data collection and results. However, the categories in which many of the studies recorded their lowest mean scores where related to the reporting of sampling methods and ethical approvals.

In the sampling category, the scores were generally lower because most of the included studies reported using a convenience sample comprising university students, rather than a random sample drawn from the general population. Furthermore, in all but three studies, the general lack of information concerning the participants made it unclear as to which population the results should be generalized. The lower scores reported for the ethics category were generally attributable to the lack of a statement; i) indicating that the study's methods had received approval from a Human Research Ethics committee (17 studies, 74%); and/or ii) outlining that informed consent was obtained from all participants (16 studies, 70%).

3.4 Article assessment

For the studies included in this review, the mean age of the participants included in the studies (Table 1) ranged from 14 months (Adolph & Avolio, 2000) to 32.7 years (Experiment 1 by Franchak & Adolph, 2014). Of the 23 included papers, 11 studies reported on the mean age of their participants (47%). Twelve studies (52%) did not specifically report the mean age of their participants; although two (9%) of these did report age ranges, which indicated that the participants were all under 32 years of age. Furthermore, nine of the studies (39%) that did not report a mean age or age range for their participants did state that they recruited a student-based sample. Finally, one study (4%) by Linkenauger, Bülthoff, and Mohler (2014) provided no indication as to the age of their participants.

In 15 of the studies (65%), the experiment was set in a real-world environment, while the remaining eight studies (35%) were set in virtual reality. While the specific response type used for each of the real-world and virtual reality studies tended to differ, it typically conformed to one of four response types. Specifically, six of these studies (26%) investigated continuous 'movement control' and three investigated 'action judgements' (13%), in which participants were required to judge the achievability of an affordance (possible or impossible) and respond by acting on an affordance when it was deemed possible. A further 12 studies required participants to make a 'conscious judgement' (52%), in which affordances were not acted on, but rather a verbal or simplified (e.g. button-press) response was given to indicate whether an affordance was possible or impossible. The remaining two studies (9%) involved a 'matching' task, which required participants to indicate the size of an action-relevant object in their environment, following manipulation of their action capabilities (Table 1). For simplicity, the following sections are organized to collectively present and analyze the results of the studies that used each of these different response types.

3.4.1 Movement control

The six studies that evaluated continuous movement control were all conducted in a virtual reality environment. Four of these studies manipulated the participants' action capabilities within the virtual environment (Bastin, Fajen, & Montagne, 2010; Fajen, 2005c, 2007b, 2008), while the remaining two studies manipulated their actual action capabilities in the real-world setting (Nakamoto, Ishii, Ikudome, & Ohta, 2012; Scott & Gray, 2010).

The two studies that manipulated the participants' actual action capabilities both investigated the adaptation of professional baseball players to baseball bats of varying mass. Both studies showed calibration to the new bats to occur. Nakamoto et al. (2012) reported recalibration to take three swings of a weighted bat, whereas Scott and Gray (2010) reported that five swings were required to calibrate to lighter bats than usual and ten swings were required for heavier bats. In contrast, the other four studies manipulated the maximum speed (Bastin et al., 2010) or braking capabilities (Fajen, 2005c, 2007b, 2008) of a vehicle in a virtual driving simulator. In each of the simulated tasks, the participants were required to calibrate to the vehicle's new capabilities. All four of the virtual driving studies showed that participants controlled their motor behavior by taking their vehicle's maximum (speed / braking) capabilities into account.

3.4.2. Action judgement

The three papers that assessed action judgements were set in a real-world environment (Adolph & Avolio, 2000; Franchak & Adolph, 2014; Ishak, Adolph, & Lin, 2008). Two of these studies showed that action judgements were accurate for tasks that involved participants fitting their hand through an opening (Ishak et al., 2008) or attempting to pass through different sized doors with different belly sizes (Franchak & Adolph, 2014). Furthermore, both of these studies provided evidence of recalibration when the dimensions of the body and/or environmental were manipulated. Franchak and Adolph (2014) found that experience in passing through doorways with experimentally-manipulated belly size helped to increase judgement accuracy.

The third study, by Adolph and Avolio (2000) assessed how 14 months old children (re)calibrate their ability to descend slopes. Their results show that these young children were able to adjust to alterations in body weight (manipulated by a weighted vest). Children seemed to use exploratory movements to assess the risks of the descent.

3.4.3 Conscious judgement of action boundary

Twelve studies investigated participants' conscious judgement of the boundaries to their action capabilities (Bourgeois, Farnè, & Coello, 2014; Fajen & Matthis, 2011; Hirose & Nishio, 2001; Linkenauger et al., 2014; Mark, 1987; Pepping & Li, 2000, 2008; Pijpers, Oudejans, & Bakker, 2007; Regia-Corte & Wagman, 2008; Thomas & Riley, 2014; Wagman, Taheny, & Higuchi, 2014; Wagman, 2012). Of these studies, two required participants to determine the boundaries of their action capabilities in a virtual environment (Fajen & Matthis, 2011; Linkenauger et al., 2014), while ten assessed this judgement during real-world tasks (Bourgeois et al., 2014; Hirose & Nishio, 2001; Mark, 1987; Pepping & Li, 2000, 2008; Pijpers et al., 2007; Regia-Corte & Wagman, 2008; Thomas & Riley, 2014; Wagman et al., 2014; Wagman, 2012).

The studies by Hirose and Nishio (2001) and Mark (1987) investigated the effect of manipulating leg length and eye height by placing 10-cm blocks under the participants' feet. For these studies, the height of a chair (for sitting judgements) or bar (for stepping judgements) was systematically raised or lowered and participants were asked to make a judgement as to when they perceived the height of the chair/bar to be at their new maximum capabilities (e.g. the bar's height represented the highest height that they could safely step over). Both studies reported that participants had an accurate perception of their sitting and stepping abilities after this manipulation and recalibrated to the changing task demands. Despite these findings, Hirose and Nishio (2001) found systematically different judgements between those trials in which the height of the seat or bar was incrementally increased and those trials in which the height was systematically decreased.

Seven of the remaining papers investigated the effect of manipulating participants' reaching capabilities and reported that one's perception of reachable space is rescaled to their action capabilities (Bourgeois et al., 2014; Pepping & Li, 2000, 2008; Pijpers et al., 2007; Thomas & Riley, 2014; Wagman et al., 2014; Wagman, 2012). Furthermore, if this manipulation was made by using a tool (Wagman, 2012) or a change in posture (Wagman et al., 2014), even when these changes were not yet experienced (e.g. the tool was not held but only viewed), recalibration still occurred. Similarly, Pepping and Li (2008) showed that participants could effectively recalibrate to a reach-with-jumping task performed on different support surfaces, even without prior experience with standing on these surfaces (i.e. using only visual information only). In an attempt to explain how reachable space is recalibrated, Thomas and Riley (2014) compared the direct perception of reachable space (i.e. asking participants how high they can reach with the tool) with an additive model of reachable space (i.e. adding up the participant's perception of reach height and tool length). The direct perception of reachable space proved to better explain judgements compared to a method of using an additive model. Participants also rapidly recalibrate to changes in (virtual) arm size (Linkenauger et al., 2014), changes in the height of their center of mass (Regia-Corte & Wagman, 2008) and changes in walking speed in a virtual reality environment (Fajen & Matthis, 2011).

3.4.4. Matching

The two articles that assessed a matching task were conducted in a real-world setting (Lessard, Linkenauger, & Proffitt, 2009; Stefanucci & Geuss, 2009). These studies both showed that perception of distances is scaled to action capabilities. For instance, apertures are perceived to be smaller when the body's width is experimentally increased (Stefanucci & Geuss, 2009). Similarly, gaps to jump over were perceived to be wider when jumping capabilities were impaired by adding weights to the participants' bodies (Lessard et al., 2009). Interestingly, this relationship was only evident for gaps that were actually jumpable; hence there was no observable change in scaling for gaps that were beyond the participants' action boundaries.

3.5 Time scale and mechanism of calibration

In general, all of the included studies showed that participants calibrated to their action capabilities and a sub-group of these studies (N = 9) also provided insight into the time scale of calibration. Table 2 provides an overview of these studies and summarizes the amount of practice that is required for calibration to a change in action capabilities. The study by Fajen (2007b) showed that (re)calibration generally occurs very quickly, demonstrating that participants were able to recalibrate to altered brake strength within one second of pressing a vehicle's brake pedal. However, in the study by Mark (1987; as described in Mark et al., 1990), participants needed about 30 minutes to demonstrate calibrated judgements of their maximum sitting and stepping height after their eye height was changed by the addition of 10 cm blocks under their feet.

4. Discussion

The main aim of this systematic review was to synthesize the existing literature on perceptual-motor calibration to changes in action capabilities with a focus on understanding the effectiveness of calibration. Our results suggest that the timeframe for calibration can be highly variable, with studies by Fajen (2007b) showing that recalibration can occur with as little as 1 second of exposure to the altered conditions and other studies showed comparable rapid recalibration (Nakamoto et al., 2012; Pepping & Li, 2000). Similarly, some studies reported that not a specific amount of time was required, but that recalibration occurred with minimal experience (Franchak & Adolph, 2014; Linkenauger et al., 2014; Wagman et al., 2014). The study of Mark (Mark, 1987) illustrated the other side of the spectrum, reporting that participants needed repeated 12 judgements before they responded accurately, taking up about 30 minutes.

Given that the time required for calibration seems to be quite variable, it is important to understand why this timeframe is so variable across different situations. Of interest for this discussion, Wagman et al. (2014) showed that judgments of maximal reaching height were relatively inaccurate without feedback, even without a manipulation of action capabilities. However, the accuracy of participants' judgement of maximal reaching height was significantly improved after they were allowed to perform the actual reaching task (Wagman et al., 2014). In contrast, Mark (1987) did not allow participants to practice the skill that they were judging. While standing stationary with altered leg length, participants were required to judge maximum sitting height. This way, the only information available to participants was information generated by postural sway, not by exploring the capabilities for sitting. Perhaps it is because of this less perfect match between the explored source of information and the skill to be judged that recalibration took a longer period of time. When attempting to replicate the results of Mark (1987), Stoffregen, Yang, and Bardy (2005) reported pilot data (supported by personal communication with L.S. Mark by Stoffregen et al., 2005) that showed that the effects of calibration disappeared when the blocks were attached to the feet of participants, while sitting in a regular chair, with feet on the ground. Sitting with blocks and rising up from the chair had already provided enough information so that further calibration was not necessary; judgements were accurate at the first attempt (Stoffregen et al., 2005). Putting these findings in the context of the results summarized in Table 2, we can conclude that the time required for calibration is mainly dependent on the aptness of the information explored for calibration. When the movement itself is explored, calibration occurs rapidly (e.g. Fajen, 2007; Nakamoto et al., 2011, Franchak & Adoph, 2014, Wagman et al., 2014), but when exploration occurs using less relevant movement, calibration takes longer (e.g, Mark, 1987).

Our results showed a general lack of research investigating calibration to changes in action capabilities in older age. None of the included studies incorporated a group of participants with a mean age higher than 33 years old. Given that ageing and neurodegenerative conditions tend to degrade the quality of one’s sensory inputs, it is unclear whether the results of these earlier studies would be transferrable to older and/or clinical populations. This is an important focus for future research, especially given the potential influence of deficits in calibration on movement errors (Plumert, 1995) and falls in older adults (Luyat et al., 2008)[1].

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[1] Falls risk entails one of the mayor challenges of our modern aging society, as one in three older adults aged 65 and over is reported to fall each year (Campbell et al., 1990), resulting in significant and ever growing medical costs (Hendrie, Hall, Arena, & Legge, 2004).

If future research would identify calibration as a key factor used in prevention of age-related accidents, then the current study adds to that understanding with the knowledge of when calibration takes a variable amount of time. Older adults need to cope with decreases in their capabilities, underlining the relevance of fast recalibration. The current study shows that calibration is most efficient when actually engaging in the to-be-calibrated activity. Given that the majority of accidents, such as fall, occur during walking (Berg, Alessio, Mills, & Tong, 1997), a hypothesis for future research might be that older adults who have a high risk of falls need to engage in walking activities to aid calibration in fall prevention,.

In the past decennium, the importance of calibration has become apparent with the development of the affordance-based approach of movement control (Fajen, 2007a). Previously, calibrating perceptual and action units has been mainly investigated in the context of the affordance problem (investigating the question how we decide *what* to do), leaving the control problem (*how* to control ongoing action) to information based theories (this division had been first made by Warren (1988) and two separate research streams have developed since). According to Fajen (2005b, 2007a), information based theories would lack the ability to take a person's limit's into account. Fajen illustrated this with a series of investigations of braking in a virtual car. The results of these studies showed that participants always brake in a way that will enable them to stop in time considering their car's maximal brake power, meaning that they must have taken their car's maximal braking capabilities into account in the control of movement (Fajen, 2005a, 2005c, 2007b).

The approach of affordance-based control has shown the relevance of calibration for everyday movement control (for instance in overtaking actions (Morice, Diaz, Fajen, Basilio, & Montagne, 2015) and interception tasks (Bastin et al., 2010)). The current study adds to this understanding by providing insight into the mechanisms of calibration. Minimal experience seems to be enough to instigate calibration, as long as there is a strong match between the available perceptual-motor information and the task; in continuous visually controlled movements, this information is abundantly present.

A question that remains after this systematic review is how the perception-action system controls behavior in order to gain the appropriate amount of information to calibrate, before engaging in movement. Higuchi, Cinelli, Greig, and Patla (2006) completed an experiment that required participants to pass through apertures in a number of different conditions: walking, walking while holding a bar (with and without the ability to turn the shoulders) and while wheel chairing. They found that in the novel tasks (walking with bar and no shoulder turn and wheelchair riding), participants slowed down in the approach to the aperture. This slowing down would have allowed them to explore the relation between the width of the bar and the width of the aperture in a task unfamiliar to the actor. In contrast, the slowing down was not present in a task in which participants were well experienced: walking (with and without holding a bar), with the ability to turn. Research has shown that experience could be a relevant factor in perceiving affordances, seeming to hold effects in affordance judgements (Higuchi, Takada, Matsuura, & Imanaka, 2004; Yasuda, Wagman, & Higuchi, 2014) as well as online movement control (Higuchi et al., 2011). It would be a relevant field for future research to investigate whether experience actually improves calibration in a skill permanently or whether the process of calibrating improves in efficiency and thus occurs faster. In the context of aging, it might mean that older adults need to get more experience with accident-related situations, for instance by inducing trips and slips in a safe environment, to extend experience in the relevant skills.

Importantly, the results of the methodological quality assessment indicated that the included studies were all of a moderate to very high methodological quality, showing that the studies in this field are generally reported to a high standard. The main shortcomings identified with the quality assessment were a general under reporting with respect to the specific ‘sampling’ methods used to recruit their participants and insufficient information addressing the ‘ethical’ aspects.

In the light of the findings of this systematic review, it is important to consider that, within the current literature; there is a general degree of uncertainty regarding the amount of overlap that exists between different types of calibration. For example, in a study by Ishak et al. (2008), affordances for fit-ability were defined by judging the relationship between the size of the participant’s hand and the size of an aperture. In contrast, a study by Smith and Pepping (2010) asked participants to judge whether a ball would fit in a specific hole; hence in both studies, affordances were defined by the relationship between the size of an object (the participant’s hand or a ball) and the size of the aperture. While the affordance in both tasks is very similar, Ishak et al.’s (2008) study manipulated hand size (action capabilities), while Smith and Pepping (2010) only manipulated aperture size (manipulating in the mapping between perceptual and action units). As this review focused on changes in *action* capabilities, studies that involved environmental manipulation (e.g. Smith and Pepping, 2010) were not included. Future research might seek to establish the differences in calibration in response to the changes affecting the three fundamental components of this process (i.e. sensory information, action capabilities and the mapping of these two sources). Furthermore, it would be of interest to know whether the results from an experiment involving the manipulation of one’s action capabilities could be generalized to what might be expected if one’s sensory information was manipulated.

An obvious strength of the current study is that it used a systematic approach to assess the current knowledge on calibration. However, the results are limited by the fact that in the field of perceptual-motor research, a number of different terms can be used to describe calibration. As such, our search may be limited by the fact that it did not identify studies that used, for instance, terms such as ‘scaling’ or ‘tuning’, but that could describe the same process. Given the inconsistencies in terminology used by previous research, it is a potential limitation of this study that not all synonyms of ‘calibration’ have been included in the search of this study. However, by restricting our focus on ‘calibration’, we focus on research that identifies itself to be about calibration and with that we were able to thoroughly focus on this concept. The fact that so many related terms exist calls for a more universal use of language in this research field.

Concluding, this study shows that the time required for calibration is dependent on the effectiveness of exploration involved. For instance, exploration using postural movements to calibrate sitting capabilities requires more time (Mark, 1987) than when braking capabilities are explored while braking (Fajen, 2007b). This systematic review revealed that there was no literature on the influence of age on the effectiveness of calibration to changed action capabilities, as none of the selected studies were conducted with an older cohort. We identify this as a clear recommendation for future research, especially considering the possible implications for falls (Luyat et al., 2008), as well as other perceptual motor coordination-related accidents in older adults, and the growing theoretical interest into calibration, considering affordance based control (Fajen, 2007a).

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7. Appendices

7.1 Appendix A. Complete Search Strategy

PubMed search

("Calibration"[Mesh] OR Calibration OR Calibrations OR Calibrate OR Calibrates OR Calibrated OR Recalibrates OR Recalibration OR Recalibrations OR Recalibrate OR Recalibrates OR Recalibrated)

AND

("Perception"[Mesh] OR Perception OR Perceptions OR Perceptual OR “Visually guided” OR Affordance OR “Perceptuo motor” OR Perceptuomotor OR Sensory OR Sensorimotor)

AND

("Movement"[Mesh] OR "Motor Skills"[Mesh] OR Movement OR "Motor Skills" OR Action OR Actions)

Embase search (Ovid) (Limited to Embase only)

exp calibration/ OR (Calibration or Calibrations or Calibrate or Calibrates OR Calibrated or Recalibrates or Recalibration or Recalibrations or Recalibrate or Recalibrates or Recalibrated)

AND

exp perception/ or (Perception or Perceptions or Perceptual or "Visually guided" or Affordance or 'Perceptuo motor' or Perceptuomotor or Sensory or Sensorimotor)

AND

exp "movement (physiology)"/ OR exp motor performance/ OR (Movement or "Motor Skills" or Action or Actions)

PsycInfo (Ovid)

(Calibration or Calibrations or Calibrate or Calibrates or Calibrated or Recalibrates or Recalibration or Recalibrations or Recalibrate or Recalibrates or Recalibrated).mp.

AND

(Perception or Perceptions or Perceptual or "Visually guided" or Affordance or 'Perceptuo motor' or Perceptuomotor or Sensory or Sensorimotor).mp.

AND

("movement (physiology)".mp. or exp motor performance/ or (Movement or "Motor Skills" or Action or Actions).mp.) [mp=title, abstract, heading word, table of contents, key concepts, original title, tests & measures]

Cochrane Central Register of Controlled Trials (CENTRAL)

MeSH descriptor: [Calibration] explode all trees OR Calibration or Calibrations or Calibrate OR Calibrates or Calibrated or Recalibrates or Recalibration or Recalibrations or Recalibrate or Recalibrates or Recalibrated

AND

MeSH descriptor: [Perception] explode all trees OR Perception or Perceptions or Perceptual or "Visually guided" or Affordance OR “Perceptuo motor” OR Perceptuomotor OR Sensory OR Sensorimotor

AND

MeSH descriptor: [Movement] explode all trees OR MeSH descriptor: [Motor Skills] explode all trees OR Movement or "Motor Skills" or Action or Actions

CINAHL

(MH "Calibration") OR Calibration OR Calibrations OR Calibrate OR Calibrates OR Calibrated OR Recalibrates OR Recalibration OR Recalibrations OR Recalibrate OR Recalibrates OR Recalibrated

AND

(MH "Perception+") OR Perception OR Perceptions OR Perceptual OR “Visually guided” OR Affordance OR “Perceptuo motor” OR Perceptuomotor OR Sensory OR Sensorimotor

AND

(MH "Motor Skills+") OR (MH "Movement+") OR Movement OR "Motor Skills" OR Action OR Actions

Cochrane Central Register of Controlled Trials (CENTRAL)

MeSH descriptor: [Calibration] explode all trees OR Calibration or Calibrations or Calibrate OR Calibrates or Calibrated or Recalibrates or Recalibration or Recalibrations or Recalibrate or Recalibrates or Recalibrated

AND

MeSH descriptor: [Perception] explode all trees OR Perception or Perceptions or Perceptual or "Visually guided" or Affordance OR “Perceptuo motor” OR Perceptuomotor OR Sensory OR Sensorimotor

AND

MeSH descriptor: [Movement] explode all trees OR MeSH descriptor: [Motor Skills] explode all trees OR Movement or "Motor Skills" or Action or Actions

Web of Science search

Calibration OR Calibrations OR Calibrate OR Calibrates OR Calibrated OR Recalibrates OR Recalibration OR Recalibrations OR Recalibrate OR Recalibrates OR Recalibrated

AND Perception OR Perceptions OR Perceptual OR “Visually guided” OR Affordance OR “Perceptuo motor” OR Perceptuomotor OR Sensory OR Sensorimotor

AND

Movement OR "Motor Skills" OR Action OR Actions

SPORTdiscus

Calibration OR Calibrations OR Calibrate OR Calibrates OR Calibrated OR Recalibrates OR Recalibration OR Recalibrations OR Recalibrate OR Recalibrates OR Recalibrated

AND

Perception OR Perceptions OR Perceptual OR “Visually guided” OR Affordance OR “Perceptuo motor” OR Perceptuomotor OR Sensory OR Sensorimotor

AND

Movement OR "Motor Skills" OR Action OR Actions

7.2 Appendix B. Results from the Quality Assessment

Appendix B. Results from the CCAT quality assessment for the included papers (N = 21)

	Preliminaries	Introduction	Design	Sampling	Data Collection	Ethical Matters	Results	Discussion	Total %	Quality
Adolph & Avolio (2000)	4	3	5	4	5	3	4	4	80	High
Bastin et al. (2010)	5	5	4	2	4	3	4	3	75	High
Bourgeois et al. (2014)	3	3	2	2	4	4	4	1	58	Moderate
Fajen (2005)	5	5	4	2	5	3	4	3	78	High
Fajen (2008)	5	3	4	2	4	4	4	3	73	High
Fajen (2007)	4	4	3	2	4	3	4	4	70	High
Fajen & Matthis (2011)	4	3	3	2	4	3	4	3	65	High
Franchak & Adolph (2014)	3	5	3	3	5	3	4	2	70	High
Hirose & Nishio (2001)	4	3	3	2	5	1	4	2	60	Moderate
Ishak et al. (2008)	4	3	4	3	4	3	5	2	70	High
Lessard et al. (2009)	5	2	3	2	5	2	4	1	60	Moderate
Linkenauger et al. (2014)	5	5	3	4	5	3	5	4	85	Very High
Mark (1987)	5	5	4	1	4	2	3	4	70	High
Nakamoto et al. (2012)	3	5	4	4	4	4	3	3	75	High
Pepping & Li (2000)	5	4	5	2	4	4	4	3	78	High
Pepping & Li (2008)	4	5	4	2	4	5	4	4	80	High
Pijpers et al. (2007)	4	3	4	1	5	4	4	3	70	High
Regia-Corte & Wagman (2008)	4	3	4	1	5	3	4	3	68	High
Scott & Gray (2010)	5	5	5	4	4	2	5	4	85	Very High
Stefanucci & Geuss (2009)	3	3	4	2	4	8	4	4	65	High
Thomas & Riley (2014)	4	4	3	2	5	2	4	3	68	High
Wagman (2012)	5	4	5	1	5	2	4	5	78	Very High
Wagman et al. (2014)	5	4	5	1	5	1	4	5	75	High

Table 1. Characteristics of the included studies (N = 23)

	Experimental phase	Experimental group N (Mean age, Spread)[a]	Environment	Task nature	Manipulation achieved with
Adolph & Avolio (2000)	exp. 2	20 (14 months ± 10 days)	Real world	Action judgement	Artificial body extension
Bastin et al. (2010)		30 (18.7, SD = 0.9)	Virtual reality	Movement control	Virtual reality
Bourgeois et al. (2014)		80 (24.7, SD = 4.7)	Real world	Conscious judgement	Tool use
Fajen (2005)	exp. 1	30 (20.9 ± NR)	Virtual reality	Movement control	Virtual reality
	exp. 2	30 (19.7 ± NR)			
	exp. 3	12 (18.8 ± NR)			
	exp. 4	10 (20.6 ± NR)			
Fajen (2008)		20 (NR[b])	Virtual reality	Movement control	Virtual reality
Fajen (2007)	exp. 1	36 (NR[b])	Virtual reality	Movement control	Virtual reality
	exp. 2	24 (NR[b])			
Fajen & Matthis (2011)	exp. 3	10 (NR[b])	Virtual reality	Conscious judgement	Virtual reality
	exp. 4	15 (NR[b])			
Franchak & Adolph (2014)	exp. 1	11 (32.7, range = 25-42)	Real world	Action Judgement	Natural process and artificial body extension
	exp. 2	48 (19.9, range = 18-24)			
	exp. 3	12 (20.6, range = 18-22)			
Hirose & Nishio (2001)		16 (21.9, range = 20-32)	Real world	Conscious judgement	Artificial body extension
Ishak et al. (2008)	exp. 1	14 (21.5, range = 18.3-35.5)	Real world	Action judgement	Artificial body extension
	exp. 2	14 (20.1, range = 19.2-21.5)			
	exp. 3	18 (22.6, range = 18.5-38.1)			
Lessard et al. (2009)		18 (NR[b])	Real world	Matching	Artificial body extension
Linkenauger et al. (2014)	exp. 1	12 (NR)	Virtual reality	Conscious judgement	Virtual reality
	exp. 2	11 (NR)			
	exp. 3	12 (NR)			
	exp. 4	12 (NR)			

Table 1. (Continued)

	Experimental phase	Experimental group N (Mean age, Spread)[a]	Environment	Task nature	Manipulation achieved with
Mark (1987)		5 (NR[b])[c]	Real world	Conscious judgement	Artificial body extension
Nakamoto et al. (2012)		8 (Mean NR, range = 19-22)	Virtual reality	Movement control	Tool use
Pepping & Li (2000)	exp. 1	46 (20.2, range = 19-26)	Real world	Conscious judgement	Artificial body extension
	exp. 2	24 (20.7, range = 18-26)			
	exp. 3	26 (20.3, range = 19-27)			
Pepping & Li (2008)		24 (19.7, SD = 0.5)[c]	Real world	Conscious judgement	Artificial body extension
Pijpers et al. (2007)	exp. 1	16 (Mean NR, range = 19-31)[c]	Real world	Conscious judgement	Natural process
	exp. 2	16 (Mean NR, range = 18-29)[c]			
Regia-Corte & Wagman (2009)		9 (NR[b])[c]	Real world	Conscious judgement	Artificial body extension
Scott & Gray (2010)	exp. 1	30 (23.4, SE = 0.8)	Virtual reality	Movement control	Tool use
	exp. 2	20 (24.1, SE = 0.6)			
Stefanucci & Geuss (2009)	exp. 1	21 (NR[b])	Real world	Matching	Tool use and natural process
	exp. 2	40 (NR[b])			
	exp. 3	10 (NR[b])			
Thomas & Riley (2014)	exp. 1a	21 (19.0, SD = 1.6)	Real world	Conscious judgement	Tool use
	exp. 1b	20 (19.2, SD = 1.3)			
	exp. 2	42 (19.5, SD = 3.1)			
Wagman (2012)	exp. 1	8 (NR[b])[c]	Real world	Conscious judgement	Tool use
	exp. 2	18 (NR[b])[c]			
Wagman et al. (2014)		25 (NR[b])[c]	Real world	Conscious judgement	Tool use and natural process

NR = 'Not Reported'

[a] All age-related data is rounded to one decimal. Where no decimals are reported, these data were not provided in the original study

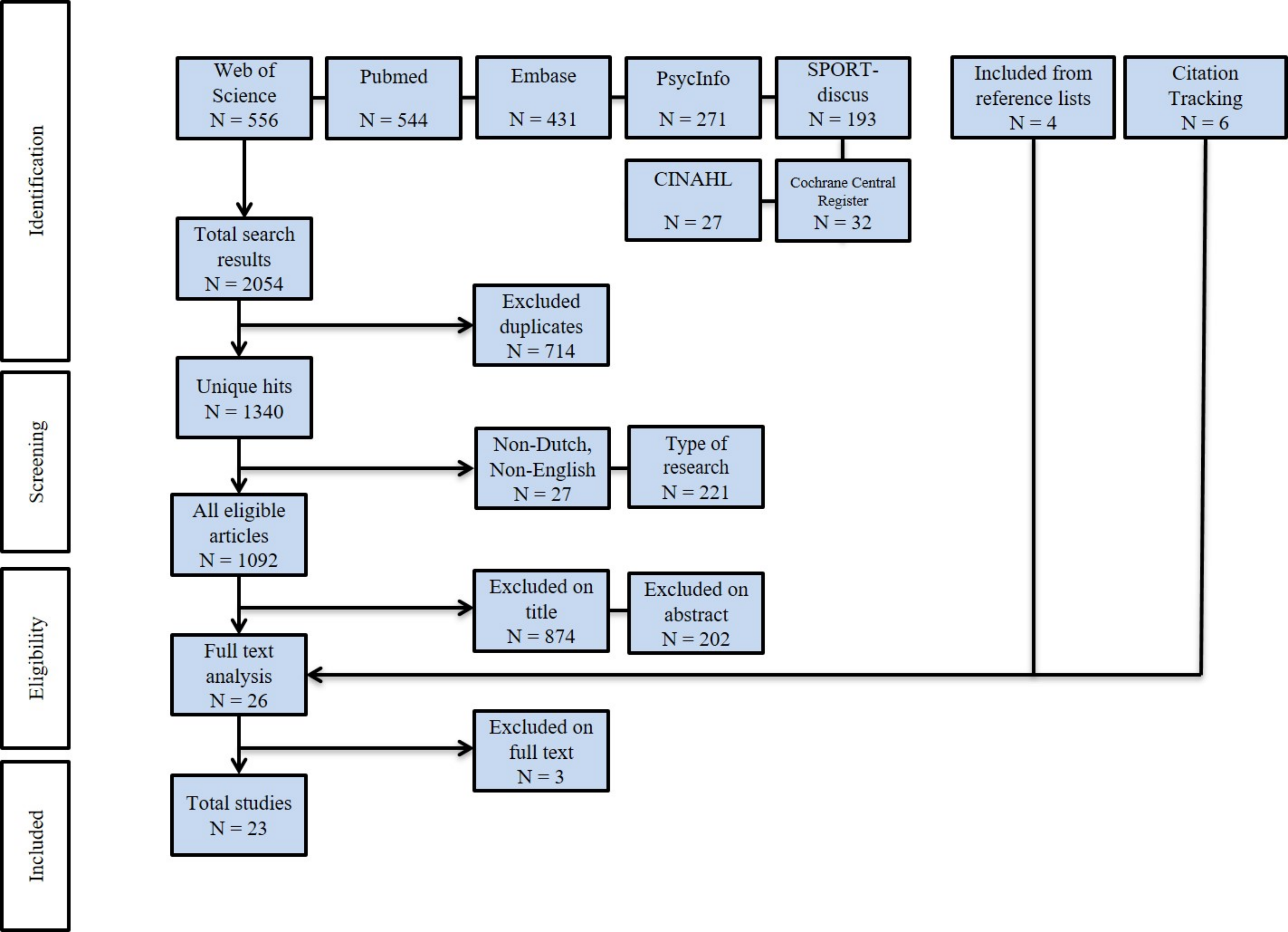
[b] Though age is not reported, it is reported that this is a student group

[c] Only female participants

Table 2. Subset of (N = 9) studies that provide insight in timescale of calibration

	Manipulation of	Timescale of calibration
Fajen (2007)	Brake strength and vision	Recalibration occurred 1 second after brake initiation, even when participants were deprived of vision
Franchak & Adolph (2014)	Belly size (pregnant and artificial)	Pregnant women (high in experience) were very accurate in their judgement of whether it was possible to pass through apertures of different sizes. Participants with artificially-manipulated belly sizes were almost as accurate as pregnant women, but only after practice. Before gaining experience with passing through apertures with an altered belly size, participants were inaccurate.
Lessard et al. (2009)	Jumping ability by ankle weights	Walking 60 meters before block of testing, to induce calibration
Linkenauger et al. (2014)	Arm size in VR	Merely having a virtually altered arm length does not recalibrate perception of reachable space, minimal experience is necessary to induce recalibration
Mark (1987)	Leg length by adding 10 cm blocks under feet	6 judgements were insufficient for rescaling, but after 12 judgements (about 30 minutes [a]) participants had recalibrated
Nakamoto et al. (2012)	Baseball bat weight	Three swings with a weighted bat was enough to induce recalibration weighted bats
Pepping & Li (2000)	Reach-with-jump height by adding weights and changing ground surface	Experiment 1: participants were instructed to jump three times and allowed to walk with weights for 3 minutes, this was sufficient to induce recalibration Experiment 2/3: participants were allowed 1 minute of experience (jumping, but not reaching) on the ground surfaces, this was sufficient to induce recalibration
Scott & Gray (2010)	Baseball bat weight	Adaptation took 5 swings for a lighter bat and 10 swings for a heavier bat
Wagman et al. (2014)	Reaching posture	6 reaches in ‘reach while stand’ posture were enough to recalibrate reaching height in manipulated posture (‘reach while kneel’ and ‘reach from stepstool’)

[a] Mark (1987) did not report on this timescale, but Mark et al. (1990, p. 327) did provide this information when discussing previous findings. They reported that in the experiment of Mark (1987), participants were allowed to walk around the room for 1-2 minutes between judgements, coming to roughly 30 minutes for 12 judgements.


Identification
Screening
Eligibility
Included
Web of Science N = 556
Pubmed N = 544
Embase N = 431
PsycInfo N = 271
SPORT-discus N = 193
Included from reference lists N = 4
Citation Tracking N = 6
CINAHL N = 27
Cochrane Central Register N = 32
Total search results N = 2054
Excluded duplicates N = 714
Unique hits N = 1340
Non-Dutch, Non-English N = 27
Type of research N = 221
All eligible articles N = 1092
Excluded on title N = 874
Excluded on abstract N = 202
Full text analysis N = 26
Excluded on full text N = 3
Total studies N = 23