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The role of movement variability and action experience in the perceptual judgement of passability

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Abstract

Perception and action are tightly coupled and previous studies have demonstrated that action experience can improve perceptual judgement. We investigated whether this improvement in perceptual judgement could be attributed to knowledge regarding movement variability being gained during action experience. Fifteen adults made perceptual judgments regarding the passability of a series of aperture sizes. These judgements were made both before and after walking through the same set of apertures (action experience). When considering the group as a whole perceptual judgement did not change after action experience. However, when splitting the group into those with low and high pre-action perceptual judgements, only those with low perceptual judgements showed an improvement in perceptual judgement following action experience and this could in part be explained by movement variability during the approach. These data demonstrate that action informs perception and that this allows adults to account for movement variability when making perceptual judgements regarding action capabilities.

Keywords

Learning by doing, movement variability, perceptual judgements, perception and action, critical ratio

Introduction

During everyday life we walk around busy environments, passing through small spaces and negotiating obstacles. In order to make these movements successfully, we must accurately perceive the environment and adjust our movements accordingly. For example, a narrow doorway might allow a child to pass through without changing their usual walking pattern, but an adult with a greater body width might need to turn his or her shoulders to walk through. In this situation the adult must recognise that a turn is needed, determine the magnitude of that turn and then accurately execute the turn at an appropriate point in time and space.

Warren & Whang (1987) found that the decision to rotate the shoulders at an aperture was based on body scaled information, and participants consistently rotate for any aperture smaller than 1.3 times their shoulder width (this is termed the 'critical ratio'). Therefore, the decision to turn or not to turn seems to be based on the size of the aperture and the size of the body. This is a finding which has been replicated in children (Wilmut & Barnett, 2011), in the elderly (Hackney & Cinelli, 2011), in novice wheelchair users (Higuchi, Cinelli, Greig, & Patla, 2006) and when moving in a non-confined space (Hackney, Vallis and Cinelli, 2013) (for a review see Higuchi, 2013). However, more recent research suggests that this is not a full explanation and that variability of body movements is also taken into account when passing though apertures (Wilmut & Barnett, 2010, 2011; Wilmut, Du, & Barnett, 2015); more specifically the variability of lateral trunk movement on the approach and variability of the shoulder rotation while passing through the aperture was accounted for. An individual with high movement variability will turn more readily compared to an individual with low movement variability. This finding is mirrored in other tasks such as stepping over objects (Snapp-Childs & Bingham, 2009). Alongside body width and movement variability other factors can influence the critical point. For example, research has demonstrated that this is larger when walking through an aperture created by humans as compared to poles (Hackney, Cinelli and Frank, 2015a) and larger when walking on an elevated or narrow path compared to a flat wide one (Hackney, Cinelli, Denomme and Frank, 2015b). The studies described above have focused on behavior at the aperture, however, Warren & Whang (1987) also considered perception of 'passability'; they demonstrated that participants could make consistent judgements regarding passability, a finding which has since been replicated (for a review see Higuchi, 2013). In a similar study, Franchak, Celano, & Adolph (2012) found that participants leave a 4cm safety margin both when judging passability and when actually passing through an aperture, therefore, these judgements are not only consistent but they are also accurate.

Several studies have considered the notion of 'learning by doing' in paradigms such as those described above. Franchak, van der Zalm, & Adolph (2010) devised a study which examined whether perceptual judgements of passability could be improved by performing a related movement. That is, could perception of whether one needed to turn for a given aperture improve after practice at actually moving through apertures? This study used an action task in which participants walked up to and through a number of apertures and a perception task where participants stood at a distance and judged whether they could squeeze through a given aperture. Participants completed both tasks, with some performing the perception task first followed by the action task (perception-first); while others completed the tasks in the opposite order (action-first). Participants in the action-first group made more accurate perceptual judgements than those in the perception-first group. The magnitude of this improved judgement was small, with the action-first group showing judgements which were 1.5cm more accurate than those in the perception-first group. Franchak et al. (2010) also found that perceptual judgements that followed action correlated with height, weight and torso size whereas those that preceded action did not. From this it was concluded that performing the action allowed participants to 'learn' to scale perceptual judgements to body height and that this resulted in the reduction in perceptual judgement error. Other studies have also shown that perceptual judgements improve following direct practice. For example, Wagman (2012) found that the underestimation in reaching height was reduced after only six attempts at a reaching task. Furthermore, Cole, Chan, Vereijken, & Adolph (2013) considered whether the perception of abilities in a range of tasks (leaping, crawling, reaching and arm swinging) improved following learning. They found that only practice of leaping resulted in an improved perceptual judgement of leaping abilities, a finding reflected by Day, Wagman and Smith (2015). To some extent all of these studies support 'learning by doing' which in turn supports Gibson's notion that movement is key to accurate perception (Gibson, 1979).

In addition to the studies described above a number of studies have examined how well we can adapt to an altered state. Franchak & Adolph (2014) asked participants to wear a 'pregnancy pack', which instantly increased the size of their bodies. Initially, perceptual judgements under-estimated the space needed, however, this was quickly recalibrated after actually walking through the doorways. Along similar lines, Hackney, Cinelli and Frank

(2014) have shown that individuals can adapt their movements when asked to carry a tray which increases their relative body width, they do this in such a way that they are able to maintain a stable critical point. Furthermore, novice wheelchair users improved perception of passability in able-bodied participants, however, it did not entirely remove underestimation of the space needed to pass (Higuchi, Takada, Matsuura, & Imanaka, 2004). Yasuda, Wagman, & Higuchi (2014) asked participants to judge passability of an aperture while holding a vertical bar (which artificially increases shoulder width) before and after action experience. The action experience was either passing through seven aperture sizes which only differed by 3cm above and below what was passable or passing through seven aperture sizes which differed by 15cm above and below what was passable. The motivation for this study was to determine whether practice only improves perception or if the practice provides opportunities to detect fine differences between passable and impassable apertures. This study found that passability judgements improved following practice and that the type of practice had no influence (Yasuda et al., 2014). Interestingly some other studies have demonstrated that when a participants' state is altered direct experience of a given task is not always necessary for the improvement of perceptual judgements. For example, Mark, Balliett, Craver, Douglas, & Fox (1990) considered the ability to judge sitting height when height had been artificially increased by attaching 10cm blocks to the feet of participants. Perceptual judgements improved after a period of walking around while wearing the blocks despite the absence of any practice at actually sitting. This finding has since been replicated (Stoffregen, Yang, & Bardy, 2005). Similarly, novice wheelchair users improve their perceptual judgements (fitting under a vertical barrier) following a period of 'practice' freely operating the wheelchair without passing under any barriers (Yu, Bardy, & Stoffregen, 2011; Yu & Stroffregen, 2012).

All of the studies described above suggest that experience of an action can influence perception. However, in order to maximize the chances of learning, these studies have used tasks which are not highly familiar; either body state was altered (Higuchi et al., 2006; Mark et al., 1990; Yasuda et al., 2014; Yu et al., 2011; Yu & Stroffregen, 2012; Hackney et al. 2014) or participants were squeezing through gaps (Franchak et al., 2010). Although we do move around our environment carrying objects which extend our body size and we do squeeze through gaps, neither of these situations are as familiar as walking around the environment unencumbered and turning to pass through gaps and apertures. Hackney et al (2015a, b), Hackney & Cinelli (2011), Higuchi et al. (2004), Warren & Whang (1987) and Wilmut & Barnett (2010) who have all considered passability, have used situations in which the participant passes through a door-like aperture, the smallest of which is usually 0.9 times shoulder width. The participant decides to rotate the shoulders to pass through rather than passing through laterally. This represents a very familiar task. Therefore, this study will consider action experience on a similar aperture task.

One important consideration regarding all of these studies is how does action experience improve perceptual judgement? The studies described above have suggested that this is due to an improved ability to judge either body dimensions or body size in relation to an external stimulus. However, one explanation which has not been previously considered is whether such action experience has any influence on our judgement of absolute size, unrelated to knowledge of body size (i.e. simply judging whether one object is larger or smaller than another object). Previous research has demonstrated that action can influence perception in many ways, for example head motion can influence the perception of 3D shape, exploration with the hands can improve depth perception and locomotion can update spatial maps even in the absence of vision (for a review see Wexler and von Boxtel, 2005). However, it is not clear whether absolute perceptual judgements can be improved following action experience, i.e. can a perceptual judgement improve with action in such a way that the improvement remains once action is ceased.

The aim of the current study was therefore three-fold, firstly to investigate whether perceptual judgements can be improved by action in a more familiar task than has been used before, walking through apertures. Unlike previous studies we did not alter body state and we will ask participants whether they can pass with or without turning the shoulders. A 'learning by doing' effect would be demonstrated by a more accurate perceived passability judgement after action experience compared to before (in line with Franchak & Adolph, 2014; Franchak et al., 2010; Yasuda et al., 2014; Yu et al., 2011; Yu & Stroffregen, 2012). When asking participants to make a perceptual judgement we asked participants whether they *would* pass without turning rather than whether they *could* pass without turning; this should ensure that passability judgements are in line with behavior. Secondly, Franchak et al. (2010) suggest that the improvement in perceptual judgement after action experience was due to the facilitation of scaling to body dimensions, as they found significant correlations between perceptual judgement and body height. Given that previous studies have shown that an action critical ratio in an aperture task takes into account movement variability (Wilmut & Barnett, 2010; Wilmut et al., 2015), we were interested to see whether action experience facilitates the use of movement variability in making passability judgements (alongside body size measures such as weight and height). Thirdly, if action did improve perceptual judgements, then a key question is does it result in a general improvement in perceptual ability for similar tasks? We included a visual estimation perceptual task both before and after the action task in order to determine whether an improvement in perception regarding passability extends to improvement in general visual perception. Given that previous studies have only found an improvement in general visual perception for active observers then it would seem unlikely for us to find an improvement in general visual perception in the current experiment given our participants will be stationary observers at this point. However, it is important to include this in order to fully consider this possibility.

Method

Participants

A group of 15 adults (4 men and 11 women) ranging from 18 years 4 months to 31 years 2 months years of age (mean= 22.5years, SD= 3.65) were recruited from *author's institution* and received course credits for participation. All participants self-reported a typical level of motor skill and all had normal or corrected-to-normal vision. This study was approved by the *author's institution* Research Ethics Committee and all participants can informed consent prior to participation.

Apparatus and procedure

Initially several anthropomorphic measures were taken: shoulder width (the distance between the left and right acromion process); body width (the widest point on the upper body); weight and; standing height. Participants performed three tasks (two of which were repeated) over five blocks conducted in the following order: 1). Visual Matching Task (pre-action); 2). Action Judgment Task (pre-action); 3). Action Performance Task; 4). Action Judgment Task (post-action); 5). Visual Matching Task (post-action).

INSERT FIGURE 1 HERE

<u>Visual Matching Task</u>

The participant stood 7m away from two apertures which were formed by three wooden partitions (2m x 0.8m). The partition in the middle was static, but the partitions at right and left could both be moved by an experimenter to create different sized apertures. See Figure

1A for an illustration of the set-up. On each trial one of the two apertures was set at a standard size of 60cm wide, this standard aperture was not changed for the duration of the trial. The other aperture (non-standard) was initially set at either 100cm wide (decreasing condition) or 20cm wide (increasing condition). The participant was asked to judge whether the apertures where the same or different in size. Each time the participant stated they were different in size the non-standard aperture was decreased by 2cm (decreasing condition) or increased by 2cm (increasing condition). The trial ended when the participant stated that the apertures were the same size. The size of the non-standard aperture at this point was recorded. From this we calculated absolute error (unsigned difference between the non-standard and 60cm), constant error (signed difference between the non-standard and 60cm) and variable error (the standard deviation of absolute error). There were 8 trials in the task, with 4 decreasing trials and 4 increasing trials. The standard aperture was on the right for half of these trials and on the left for the other half. Between trials participants turned away from the partitions to avoid seeing the aperture in relation to the experimenter.

<u>Action Judgement Task</u>

In this task participants stood 7m away from the center of an aperture formed by two sliding partitions (2 m x 0.8 m). At the start of each trial the aperture was set at either a shoulder aperture (SA) ratio of 2.1 (decreasing condition) or a shoulder aperture ratio of 0.9 (increasing condition). That is the size of the aperture was either 2.1 times shoulder width or 0.9 times shoulder width. The participant was asked to judge whether they would need to turn their shoulders to walk through the aperture, stating 'turn' if they thought they would need to turn and 'straight' if they thought they did not need to turn (i.e. they thought they could walk straight through). After each judgement the aperture decreased by 2cm (decreasing condition) or increased by 2cm (increasing condition). The point at which the participant's judgement switched from 'straight' to 'turn' (decreasing condition) or 'turn' to 'straight' (increasing condition) was the point at which the trial ended. The size of the aperture at this point was recorded. Perceptual critical ratio was calculated for each participant individually, this was done by plotting shoulder to aperture (SA) ratio when the trial ended against the proportion of times that SA ratio was perceived as needing a turn (from 0% to 100%). A third order polynomial curve was then fitted to each participants' data and the equation of this curve used to determine the critical SA ratio at which a participant perceived a turn was needed on 50% of trials. This fitting process resulted in a mean R^2 of 0.89.

Buffer, the difference between the aperture at perceptual critical ratio and shoulder width, the constant error (the signed difference in aperture size at perceptual critical ratio compared to action critical ratio) and the absolute error (the unsigned difference in aperture size at perceptual critical ratio compared to action critical ratio) was also calculated. See Figure 1B for an illustration of the setup. There were 6 trials in the task, with 3 decreasing trials and 3 increasing trials. Participants turned away from the partitions between trials.

Action Performance Task

In this task, participants were asked to walk through the aperture set at different sizes. The set up is as shown in Figure 1B. A 12 camera Vicon motion capture system (Oxford Metrics) running at 100 Hz was used to track the movement of three reflective markers (9.5 mm in diameter) placed on the left and right acromion process (LAP and RAP, respectively) and on the seventh cervical vertebrae (C7). In order to determine the point at which the participant reached the aperture, markers were also placed on the inner edge of the partitions. The relative sizes of the six shoulder aperture (SA) ratios (0.9, 1.1, 1.3, 1.5, 1.7, and 1.9) were calculated for each participant (based on the measurement of shoulder width). On each trial, participants were asked to stand behind the start point (7m from the aperture) and focus on a red circle on the floor in front of their feet. On initiation of a trial, participants were instructed to look up and walk, at a self-selected pace, through the aperture to the stop point (2m past the partitions). Movement was captured from the point at which C7 was 4m from the partitions onwards, thus allowing the participant to have reached a natural walking pace prior to the start of movement capture. On returning to the start point (by passing around the back and to the right of the partitions), participants were told to focus on the circle and not look up until instructed to do so. While the participant returned to the start point, the experimenter changed the aperture size by sliding the partitions closer together or further apart in accordance with a measure placed on the floor. An experimenter moved the start point by ±20cm to prevent participants from executing a learnt movement resulting from a constant distance between start point and partitions. No specific instructions were given on how participants should act when an aperture was too small for them to walk through normally; however, when demonstrating the task, the experimenter passed through a narrow aperture by rotating the shoulders. Each aperture ratio was presented 5 times (total of 30 trials per participant) in pseudo-randomised order, whereby the same aperture was not used on two or more consecutive trials and aperture size did not predictably increase or decrease.

All participants successfully passed through each aperture size without colliding with either partition. Vicon movement data were filtered using an optimised low pass Woltring filter with a 12Hz cut-off point and then analysed using tailored MatLab routines. In order to determine *action critical ratio* shoulder angle at the door (angle created between LAP and RAP with respect to the frontal plane at the point C7 passed through the partitions) was calculated. For each trial we determined whether a turn had occurred: a turn was classified as when shoulder angle at the door was greater than 3 SD above baseline sway (the mean angle created between LAP and RAP with respect to the frontal plane over the first 2 seconds of movement). For each participant, a third order polynomial curve was then fitted to SA ratio plotted against the proportion of turns for that SA ratio (curve fitting resulted in an average R^2 of 0.90). The equation of the curve then used to determine the critical SA ratio at which a participant turned on 50% of trials. Buffer, the difference between the aperture at perceptual critical ratio and shoulder width was calculated. Additional measures of movement variability were also calculated: *Variability of the lateral trunk movement (mm)* was the standard deviation of the average lateral movement of C7 across the first 2s of the movement; *Variability of shoulder angle at the door (^{o})* was calculated as the standard deviation of the shoulder angle at the door and; *Variability of baseline sway (^{o})* was the variability across the baseline sway for each trial. These measurements of variability were based on those we have used previously and have shown to be important in scaling movement adaptations when walking through an aperture (Wilmut & Barnett, 2011; Wilmut et al., 2015).

Results

Effect of action experience on action judgment

Initially the pre- and post- action perceptual critical ratios, the buffer, the constant error and the absolute error were directly compared using a paired samples t-test. These values can be found in Table 1. No significant difference was found in any of these measures from pre-action to post-action. Critical ratios from the action task can also be found in Table 1.

INSERT TABLE 1 HERE

Effect of action experience on visual matching

Data for the visual matching task can be found in Table 2. A one-sample t-test demonstrated that neither the pre- or post-action final judgment differed from the standard aperture size

(60cm), [Pre-action, t(14)= 1.35, p=.20; post-action, t(14)= .96, p=.36]. The three error measurements (absolute, constant and variable) were compared from pre-action to post-action to determine whether the action task had an influence on visual perceptual ability. For constant error and for absolute error no difference was seen in pre-action and post-action values [both p>.05]. However, variable error did show a decrease from pre-action to post-action [t(14)=2.27 p=.04 r=.52].

INSERT TABLE 2 HERE

Correlations with movement variability

In order to consider the role of movement variability in perceptual judgements we considered correlations between the pre- and post- SA critical ratios and lateral movement variability, baseline sway variability, angle at the door variability and body width, shoulder width, weight and height. A significant correlation was found for the post-action SA critical ratio and baseline sway variability [r=.614 p=.015], a lower sway variability indicated a lower critical ratio. In addition significant correlations were seen between post-action SA critical ratio and shoulder width [r=-.711 p=.003] and body width [r=-.526 p=.044] where a wider shoulder and body width was related to a smaller post-action judgement. The correlations for height and weight were both approaching significance. All correlation coefficients can be found in Table 3.

INSERT TABLE 3 HERE

Low and high initial judgements

On closer inspection of the pre-action judgement critical ratios it was clear there was a large range of values: from 1.09 to 1. 71. It was also apparent that those participants with lower initial critical ratios tended to increase this post-action, while those with higher initial critical ratios tended to decrease this post-action. In order to explore this finding we divided the cohort into two groups, none of the participants under-estimated the space they needed (i.e. we saw no SA ratios below 1) therefore, the groups were split into those with low pre-action critical ratios (low pre-action CR, pre-action critical ratio less than 1.5 times shoulder width N=8) and those with high pre-action critical ratios (high pre-action CR, pre-action critical ratio more than 1.5 times shoulder width N=7). A two-way repeated measures ANOVA (group x time point, pre-action, action, post-action) were carried out on the critical ratio data which can be found in Figure 2.

For critical ratio a significant main effect of group [$F(1,13)=13.81$ $p=.003$ $\eta^2=.52$] was found which was due to higher critical ratios in the low pre-action CR group compared to the high pre-action CR group. A significant main effect of time point was also found [$F(1,13)=13.78$ $p<.001$ $\eta^2=.52$. A significant interaction between time point (pre-action, action, post-action) and group was found [$F(1,13)=12.64$ $p<.001$ $\eta^2=.49$]. The interaction was investigated using simple main effects which found a significant difference in SA critical ratio pre-action across the two groups [$F(1,13)=27.16$ $p<.001$ $\eta^2=.68$] but no difference in action critical ratios or in the post action perceptual critical ratio [$p>.05$]. In order to determine whether both the low and the high pre-action CR group changed perceptual judgements, paired t-tests were used to consider the pre- to post- perceptual CR for each group separately. The low pre-action CR group increased their perceptual CR from pre- to post- judgement [$t(7)=-2.802$ $p=.027$ $r=.73$], the high pre-action CR group appeared to decrease their perceptual critical ratio from pre- to post- judgement however, this failed to reach significance [$t(6)=2.37$ $p=.056$ $r=.70$].

In addition to critical ratio, buffer size, constant error and absolute error of perceptual judgements before and after action experience were considered for the two groups separately. Only pre- and post-judgements were considered in these analyses, these data can be found in Figure 2. For all three measures a main effect of group [buffer: $F(1,13)=16.00$ $p=.002$ $\eta^2=.55$, constant error: $F(1,13)=8.40$ $p=.012$ $\eta^2=.39$, absolute error: $F(1,13)=7.87$ $p=.015$ $\eta^2=.38$] indicating a higher buffer, constant error and absolute error for the high compared to the low pre-action CR group. In addition, all three measures showed an interaction between time point and group was found [buffer: $F(1,13)=13.08$ $p=.003$ $\eta^2=.50$, constant error: $F(1,13)=13.57$ $p=.003$ $\eta^2=.64$, absolute error: $F(1,13)=6.96$ $p=.02$ $\eta^2=.35$]. To determine whether a change in buffer, constant error and absolute error was found for both groups paired t-tests were used to compare the pre- to post- values for the low pre-action CR and high pre-action CR group separately. For buffer size, the low pre-action CR group showed an increase from pre- to post action [$t(7)=-2.89$ $p=.023$ $r=.74$], indicating that following action experience this group perceived a need for a greater amount of space between their shoulders and the door when passing without turning. The high pre-action CR group showed no difference from pre- to post action experience. For constant and absolute error, the low pre-action CR group showed a significant decrease from pre- to post-action experience [constant:

t(7)=2.89 p=.023, r=.74, absolute: t(7)=2.90 p=.023, r=.74], therefore, following action experience their perceptual judgement was closer to their action critical ratio. The high pre-action CR group showed no significant change in error.

INSERT FIGURE 2 HERE

In order to determine on which, if any, metrics these two groups differed we compared the two groups (low pre-action and high pre-action perceptual judgement) on a number of factors relating to body size, movement ability and perceptual ability. These variables can be found in Table 4. Independent t-tests were carried out to look for group differences. No significant group differences were found for the perceptual ability or movement ability measures. For body size a significant group difference was found for weight [t(13)=2.25 p=.042 r=.53] with a higher body weight in the high pre-action CR group compared to the low pre-action CR group. It is worth noting that there was one participant in the high pre-action CR group with a very high weight (+2.7SD above cohort mean and +1.8SD above the high pre-action CR group mean), however, the group difference between the low and high pre-action CR group remained when this participant was removed.

INSERT TABLE 4 HERE

Discussion

The current study had three main aims: to determine whether action experience could influence perceptual judgement in a highly familiar aperture task; to determine whether movement variability was used to scale perceptual judgement tasks both before and after action experience; and if action experience can influence perceptual judgement in this task to determine whether action experience also influences absolute size judgement. Findings, in relation to these three aims, will be discussed in turn.

Action experience and perceptual judgements on a highly familiar task

When considering all participants together we found no difference in the pre- to post- action judgements. However, it was apparent that our participant cohort was made up of two distinct groups, those who had low pre-action judgements and those who had high pre-action judgements. When splitting the cohort, we saw that the low pre-action CR group significantly changed their perceptual judgements (in terms of SA ratio, buffer size and error) following action experience and this resulted in the perceptual judgements coming in line with their action performance. The change in the high pre-action group did not reach significance, however, they do show a reduction in their perceptual judgement from pre- to post-action and given the small sample size the lack of significance may simply reflect a lack of power. In their study, Franchak et al. (2010) found an overall learning effect without the need to sub divide their group. However, they do also note that half their participants under-estimated and half over-estimated. This is in line with the findings of the current study and in the current study this masked an overall learning effect. This is one of the few studies to demonstrate a change in perceptual judgements following action experience in a task that adults are highly familiar with and that is executed on a daily basis. Although previous studies have also shown that action experience can influence perceptual judgements this has only been demonstrated for squeezing through apertures (Franchak et al., 2010), able-bodied participants passing under barriers in a wheelchair (Yu et al., 2011; Yu & Stroffregen, 2012) and walking through an aperture while carrying a bar/tray (Hackney et al. 2014; Yasuda et al., 2014). This is the first study which has focused on a familiar aperture passage task and found that action experience can improve perceptual judgment despite all participants being highly practiced at the task. Previous studies also using familiar tasks have found similar effects, Wagman (2012) found that perceptual judgement of reaching height is improved after action experience and Cole et al. (2013) and Day et al. (2015) found an improvement in the perceptual judgements of leaping distance following action experience.

Interestingly, only the group that had low pre-action perceptual judgements showed a change in their perceptual judgements from pre- to post-action. Previous studies which have looked to explain why participants may over-estimate the need to turn have suggested this may be due to perceptual error (Wraga 1999). However, Franchak et al. (2012) raised the possibility that an over-estimation may indicate a sensitivity to the space needed to walk and that a walker will combine factors such as the probability of success (i.e. passing without collision) with information regarding penalties for error (i.e. the harm that could come from collision). In the current study we see that the participants with a low pre-action perceptual judgement (i.e. those more at risk of collision) re-calibrated their perceptual judgements within the time frame of the experiment. This may be because the cost of under-estimating the space needed is greater than over-estimating the space needed to pass. Couching this in terms used by Franchak et al. (2012) we can think of the probability of success being lower for the low pre-action CR group, therefore, by changing their perceptual judgement following action experience they were increasing the probability for success. Although the group that had high pre-action perceptual judgements had a high probability of success there is a potential energy and time cost to greater turning of the shoulders, therefore, we suggest that the high pre-action perceptual judgement group may have shown a significant effect had the participants been given longer to re-calibrate their judgements. Support for this conclusion, comes from Hackney et al. (2014). Their study primarily considered how participants re-calibrated their movements while passing through (or around) an aperture when they were given a tray to carry which altered their body width. Tray size changed throughout the experiment, forcing participants to continually re-adapt. Alongside the finding that participants adapted very well to these changes the authors identified that some participants were able to re-calibrate their responses very quickly, while other participants did this more slowly. Pertinent to our findings was the observation that those participants who were slow to re-calibrate were also those who over-estimated the space needed to pass. Therefore, the over-estimation of space may be linked to how quickly a judgement can be re-calibrated following either action experience or an adjustment to body size.

We explored some of the reasons why some people may have shown a high pre-action judgement while others showed a low pre-action judgement. Stefanucci & Geuss (2009) found that broad-shouldered participants under-estimated the width of an aperture while narrow-shouldered participants over-estimated this. In the current study we identified weight as the only factor which differed across the high and low pre-action group. The lack of a shoulder width difference across these groups may simply be due to limited variation in this factor in our sample. Our findings suggest that weight may be tied to initial perceptual judgement of space needed to pass.

The role of movement variability in perceptual judgements

In previous studies it has been demonstrated that typically developing adults and children both incorporate movement ability into their passability actions. A participant with a high lateral trunk movement leaves a larger safety margin than a participant with a low lateral trunk movement (Wilmut & Barnett, 2011; Wilmut et al., 2015). In their studies Franchak & Adolph (2014) and Franchak et al. (2010) reported significant correlations between post-action judgment and height, weight and torso size. They suggest that action experience helps participants to scale perceptual judgements to aspects of body size and this makes their later perceptual judgements more accurate. In the current study, we found significant correlations between post-action perceptual judgements and movement variability and also between post-action perceptual judgements and body / shoulder width. We did not find any correlations between perceptual judgement and height, weight or body width. These findings suggest the reduction in error of perceptual judgement following action experience is linked to movement variability. Therefore, action experience helped participants to scale their post-action perceptual judgements to movement variability and body/shoulder width. In the current study, aperture size at critical point during the action task and aperture size at critical point during the pre-action perceptual task differed by 6.3cm and then during the post-action perceptual task by 4.2cm. This finding demonstrates that although action experience results in more accurate perceptual judgements there is still some degree of error. This may be reduced further with a greater amount of action experience. Franchak et al. (2012) found a similarly measured error of 4cm prior to any action experience demonstrating a more accurate representation prior to specific experience in the Franchak cohort. The reason for this is most likely due to the fact that different tasks were used across the two studies.

In contrast to Franchak et al. (2010) we did not find that post-action judgements were related to standing height, weight or body width. This could also relate to differences in the tasks employed. In Franchak et al.'s (2010) study participants were asked to 'squeeze' through a narrow gap, this often required a participant to compress their body. This is an unusual task and one that participants will have had limited experience of; therefore, the action experience may have helped them to realize the helpfulness of height, weight and body size as metrics for making perceptual judgements. In the current study we asked participants to walk through apertures, the smallest of which was only just smaller than shoulder width. This is a highly practiced task; we do this while walking through doors, past pedestrians, around street furniture etc. on a daily basis Therefore, the use of these body metrics may already be well established and not variable enough across our participants to demonstrate a relationship.

<u>Action experience and judgements of absolute size</u>

In terms of the visual matching task we saw a decrease in variable error following action experience. Despite this change in variable error participants did not become more accurate in their judgements (we saw no change in absolute error), they simply became more consistent with their judgements. A reduction in variable error such as this could simply be due to exposure of the task over a period of time (Muller & Sternad, 2009). The fact that participants did not become more accurate on the visual matching tasks suggests that the change we see in passability judgements is not simply due to an overall improvement in perceptual ability following action experience, but rather there is something specific which improves passability judgements. However, it is important to be cautious drawing this conclusion as it is possible that the lack of improvement in the absolute error may be due to a ceiling effect within this task.

Limitations

The current study has two main limitations. The perceptual judgements in this study were measured using a method of adjustment (i.e. the participant viewed the aperture as it was adjusted to either be smaller or to be larger). This method has been used widely in studies considering similar judgements (for example: Day et al., 2015; Cole at al., 2013; Mark et al., 1990; Yasuda et al. 2014; Yu et al., 2012; Yu et al., 2011; Warren and Whang, 1987). However, an alternative method, such as that employed by Franchak et al. (2010) and Franchak et al. (2012) is to present participants with one aperture size at a time and ask for a single judgement. Furthermore, in the current study we asked participants to complete six judgement trials before action experience and six judgement trials after action experience. Previous literature provides no real gold-standard in terms of number of trials and this ranges from less than used in the current study (for example Cole et al., 2013 and Yasuda et al. 2014) to the same number used (for example Day et al. 2015) to a great deal more (for example Franchak et al. 2010 and Franchak et al. 2012). The methodological decisions made in the current study were mainly driven by the majority of previous research. Our data, in terms of standard deviation of response suggest a suitable level of variability which indicates a sufficient number of trials. However, we concede that using a more conservative method of judgement estimation (in terms of reducing response bias but avoiding a method of adjustment) and including a greater number of trials would ensure a greater reliability and a more accurate representation of perceptual judgement both before and after action experience.

Conclusions

In conclusion, our results demonstrate that individuals are able to use movement experience to improve the accuracy of their passability judgments about action possibilities. It would seem that action experience allows participants to ‘tune’ their perceptual judgements to their movement variability and body size in a way that was not apparent prior to movement experience. However, this seems to be influenced by initial judgement, with only those participants showing a low pre-action perceptual judgement adapting their judgements following action experience. An important next step would be to consider how perceptual judgements in more complex aperture crossing situations can be influenced by movement experience. For example, comparison of an aperture created by humans versus poles (as used by Hackney et al, 2015a) or comparison of an elevated or narrow pathway leading up to an aperture (as used by Hackney et al. 2015b).

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Table 1. Critical ratios (CR) for the pre-action, action and post-action judgement task. Standard deviation is given in brackets.

	Shoulder to aperture ratio (SA)	Buffer size (cm)	Constant error (cm)	Absolute error (cm)
Pre-action perceptual	1.42 (0.18)	15.68 (6.49)	5.04 (6.35)	6.29 (5.01)
Post-action perceptual	1.46 (0.09)	17.21 (2.89)	3.59 (3.63)	4.20 (2.86)

Table 2. Data from the visual matching task. Standard deviation is given in brackets.

	Pre-action	Post action
Final judgment (cm)	60.5 (1.34)	60.5 (1.93)
Absolute error (cm)	3.57 (1.57)	2.98 (1.73)
Constant error (cm)	0.44 (1.36)	0.48 (1.93)
Variable error	4.45 (1.81)	3.68 (1.58)*

*p<.05

Table 3. Correlation coefficients between pre and post judgements and measures of body size and movement variability. **p<.001 *p<.05

		Measures of movement variability			Measures of body size			
		Lateral movement	Baseline sway	Angle at the door	Shoulder width	Body width	Weight	Height
CR	Pre-action	R=-.18 p=.52	R=.08 p=.79	R=-.14 p=0.62	R=-.25 p=0.37	R=0.47 p=.87	R=.36 p=.19	R=-.31 p=.27
	Post-action	R=-.40 p=.14	R=.78 p=.001**	R=-.03 p=.90	R=-.71 p=.003*	R=-.53 p=.04*	R=-.49 p=.06	R=-.51 p=.05

Table 4. Body size, movement ability and perceptual ability measurements for the under-estimating and over-estimating pre-action judgement groups. Standard deviation is given in brackets.

			Low pre-action judgement	High pre-action judgement
Body size	Height (cm)		169 (5.93)	164 (4.90)
	Weight (kg)		54.0 (7.05)	68.7 (16.98)*
	Body width (cm)		44.1 (2.6)	43.7 (5.1)
	Shoulder width (cm)		38.3 (1.8)	36.7 (2.6)
Movement ability	Lateral movement variability (cm)		1.49 (0.28)	1.50 (0.25)
	Baseline sway variability (^{o})		1.99 (0.62)	2.20 (0.79)
	Shoulder angle at the door variability (^{o})		7.04 (3.03)	7.20 (1.68)
Perceptual ability	Absolute error (mm)	Pre-action	3.93 (1.85)	3.14 (1.16)
		Post-action	3.03 (1.61)	2.91 (1.99)
	Constant error (mm)	Pre-action	0.77 (1.01)	0.07 (1.67)
		Post-action	0.34 (0.73)	0.63 (2.82)
	Variable error (mm)	Pre-action	4.89 (2.35)	3.84 (0.64)
		Post-action	4.06 (1.95)	3.23 (0.98)

* p<.05

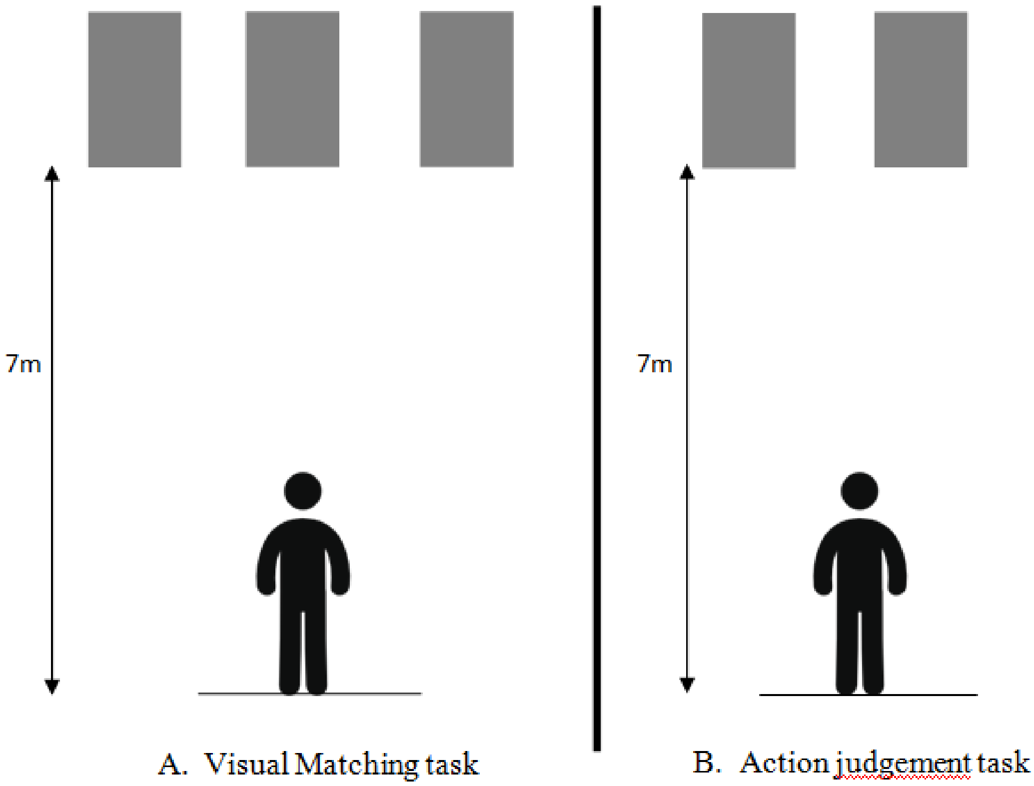

Figure 1. A. An illustration of the set-up for the visual matching task. B. An illustration of the set-up for the action judgement task and action performance task

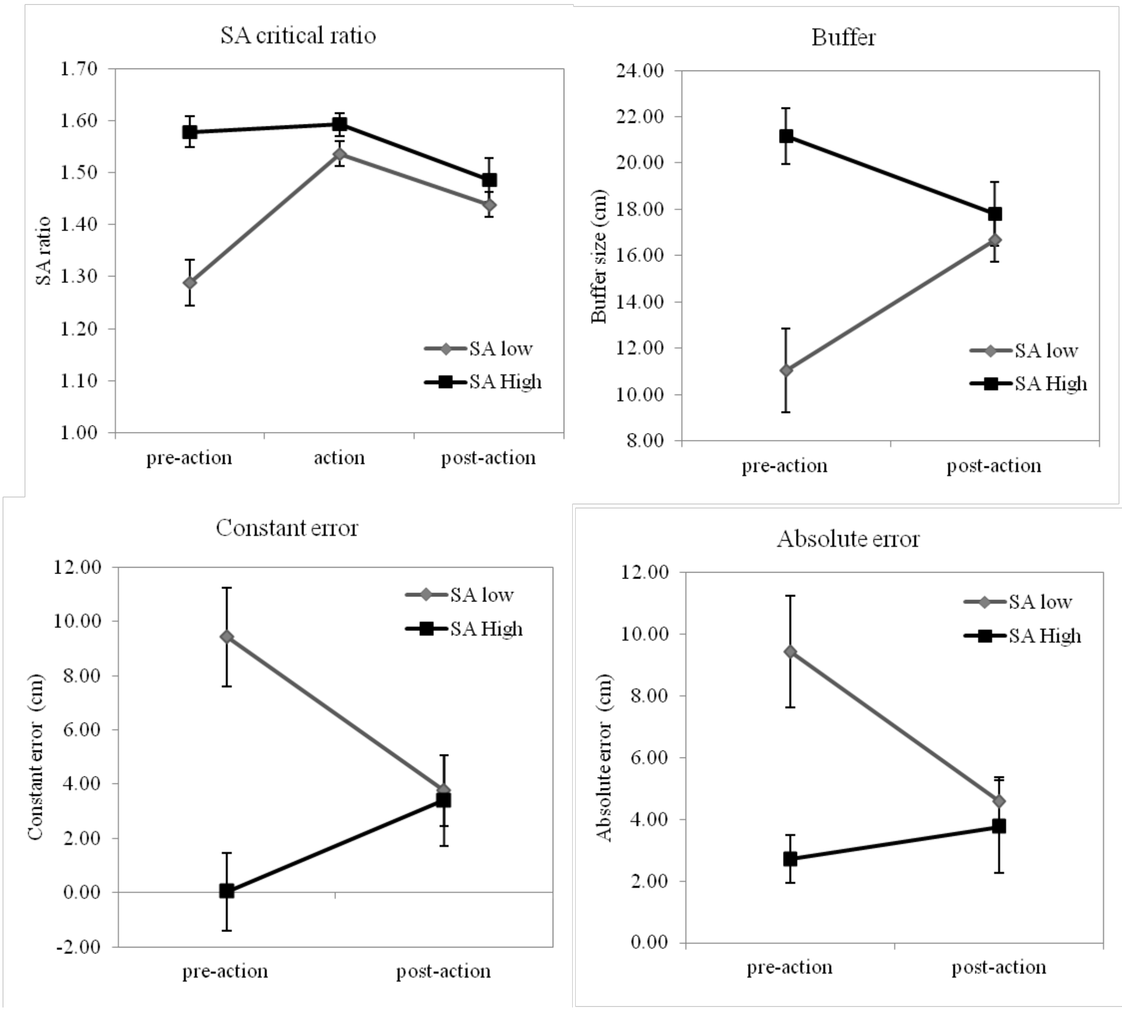

Figure 2. SA critical ratio across pre-action, action and post-action for low- and high- pre-action ratio groups. Buffer, constant error and absolute error across pre-action and post-action for low- and high- pre-action ratio groups. Error bars are standard error.