# Expert performance by athletes in the verbal estimation of spatial extents does not alter their perceptual metric of space

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**Abstract.** Athletes often give more accurate estimates of egocentric distance along the ground than do non-athletes. To explore whether cognitive calibration was accompanied by perceptual change, athletes and non-athletes made verbal height and distance estimates and also did a perceptual matching task between perceived egocentric distances and frontal vertical extents. Both groups were well calibrated for height estimation for poles viewed frontally, but athletes were much better calibrated at estimating longer egocentric distances (which are systematically underestimated by non-athletes). Athletes were more likely to have learned specific units of ground distance from relevant sports contexts. Both groups reported using human height as a metric for vertical extent. For non-athletes, verbal underestimation of ground distance corresponded to predictions based on perceptual matches between egocentric distances and vertical extents in conjunction with human-height-based verbal estimates of vertical extents. For athletes, the verbal scaling of egocentric distances of 10 m or more was more accurate and was not predicted by their egocentric distance matches to vertical extents.

**Keywords:** distance estimation, egocentric distance, height perception, spatial biases, non-Euclidean, visual space.

## 1 Introduction

Do athletes see distances and heights differently than non-athletes? Do they judge them differently? Many forms of athletic competition take place in highly standardized spatial settings. In basketball, for example, the standard height of 10 feet (3.05 m) describes the regulation height of the rim both for men's and for women's basketball, and this fact is well known among players. In baseball, it is widely known that the distance to first base is 90 feet (27.4 m). The combination of experiential knowledge of standardized heights and distances with explicit knowledge of their nominal dimensions may provide a basis for cognitive calibration of distance and height estimation among athletes that is not afforded to most adults. It has typically been found that egocentric ground distances are underestimated by verbal report (eg, Foley et al 2004), and recently it has been shown that this verbal underestimation of egocentric distance along the ground can be captured by spatial matching tasks (Li et al 2011). We sought to compare athletes and non-athletes in spatial estimation performance and spatial matching performance to examine how the two are related.

We emphasize that we have no reason to expect that skilled athletic performance depends on the accurate verbal estimation of distance, except, perhaps, in sports like golf, where explicit knowledge of distances and slants may be used in planning performance. There is some evidence that golfers are much more accurate than others in estimating distances on grass (eg, Durgin and Li 2011). If athletes tend to have greater opportunity for cognitive

calibration of perceptual experience based on greater direct experience of known extents, the question arises whether their perceptual experience is fundamentally altered by this knowledge. That is, if athletes are more accurate at estimating heights and egocentric distances, is their performance in perceptual matching of height and egocentric distance also affected?

Durgin and Li (2011) asked participants to estimate their gaze declination toward targets presented on a slanted field or suspended in space in virtual reality. They found that explicit perceptual estimates of angles overestimated deviations from horizontal gaze by a factor of 1.5, and argued that this expanded angular perception might reflect the maintenance of higher angular coding precision in the central part of vision. The expansion was not limited to verbal estimation but was reproduced by participants who were asked to set a suspended ball viewed from an elevated eye-height to a visual direction that bisected horizontal and vertical. The average perceived bisection direction was 31° below horizontal. Durgin and Li pointed out that the verbal underestimation of egocentric extents might be related to this overestimation of angular declination. In a post-hoc analysis, they found that verbal estimates of distance collected during their study differed between golfers and non-golfers (with golfers making accurate estimates while non-golfers underestimated egocentric distances by a factor of about 0.7), but that estimates of angular declination did not differ as a function of golf experience.

The possible role of angular declination as a reliable source of egocentric distance estimation has been recognized for some time (eg, Wallach and O'Leary 1982), and recently confirmed in virtual reality (Messing and Durgin 2005) as well as in natural environments (Ooi et al 2001). However, the notion that frequently observed biases (underestimation) in egocentric distance perception might be the result of functional biases in perceived gaze declination has only recently been suggested (Durgin and Li 2011; Li and Durgin 2010). Li et al (2011) tested the gaze declination model of egocentric distance underestimation using a perceptual matching task in which participants adjusted their distance from a vertical pole until they believed that their distance matched the height of the pole. They conducted an outdoor version of the study as well as a version in an immersive virtual environment. Similar data were collected by Higashiyama and Ueyama (1988). Using the empirically derived gain of 1.5 for perceived gaze declination, Li et al found that a parameter-free geometric model based on misperceived gaze declination (and elevation) fit both their own perceptual matching data as well as the data of Higashiyama and Ueyama nearly perfectly. The perceptual matching model is illustrated in Figure 1. Li et al argued that the relative perception of vertical extents and egocentric extents could be understood in terms of biases in perceived angular declination (and elevation).

Reviews of studies of verbal estimation of distance generally show that participants' egocentric distance estimates are proportional to distance (when fit with a power function, they have an exponent very close to 1), but that verbal reports tend to underestimate distance by a factor between 0.7 and 0.9 (eg, Da Silva 1985; Loomis and Philbeck 2008). This kind of underestimation of distance is consistent with the gaze declination model and with matches between frontal vertical extents and egocentric distances. There is much less data concerning the explicit estimation of heights, though it is generally believed that vertical extents appear taller than they are (the vertical horizontal illusion; Higashiyama and Ueyama 1988; Kammann 1967).

In the present study we sought to evaluate the expertise of college athletes in the estimation of distance and height and to compare their estimation performance with non-athletes. In the same study we compared athlete and non-athlete performance on two action measures (walking and throwing) and on perceptual matching between vertical extents and
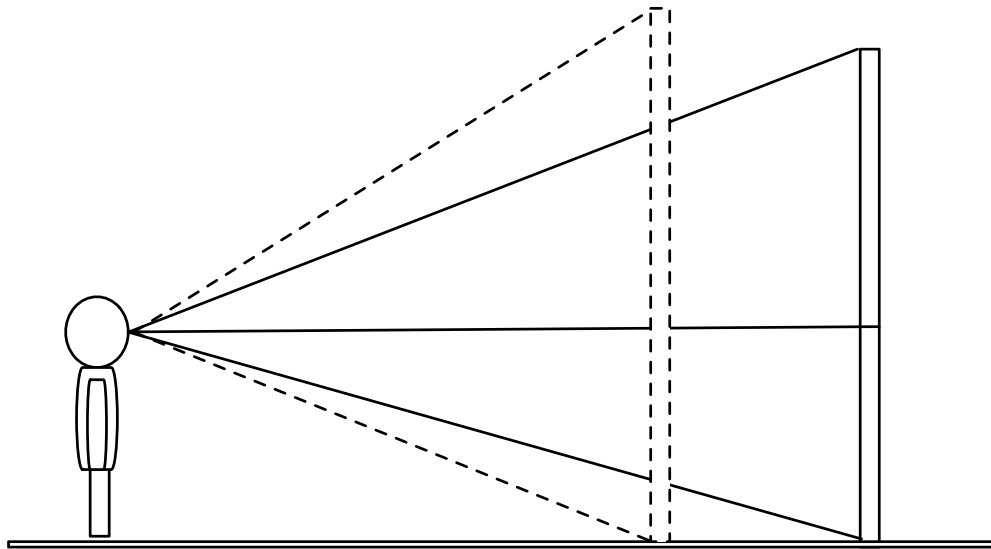
**Figure 1.** An illustration of a model of egocentric distance and height matching based on measured biases in perceived angular elevation and declination of gaze. The physical situation at the point of a perceived match between pole height and egocentric distance is depicted by the solid lines. These lines represent a vertical pole and the angular directions from the observer's eye to the top, eye-height level, and base of the pole. The dashed lines represent the imputed perceptual experience at the subjective matching point based on prior evidence that gaze declination and gaze elevation are exaggerated with a gain of about 1.5. Biases in perceived directions of gaze, in combination with eye-height, define the perceived egocentric distance and height of the pole geometrically. The model accounts quantitatively for dramatic biases observed in matches between egocentric distance and vertical extents. Eye-height (human height) can provide the scale for both height and distance. Note that angular distortions leading to the expanded angles shown by the dashed lines compress perceived egocentric distance substantially but, as illustrated, do not have much effect on perceived height at the apparent equi-distance point.

horizontal extents. We originally suspected that basketball players would be more likely to have specialized knowledge about height while field athletes might have specialized knowledge about distance. Because performance on action measures such as walking and throwing is normally quite good, we expected that biases in action measures and perceptual matching tasks might not differ as a function of athletic experience.

## 2 Method

Twenty-six varsity athletes (14 female) and 23 other students (12 female) participated for pay. Eleven of the varsity athletes (9 female) were basketball players. Ten played lacrosse. Two were on the track team. The remaining three played golf, baseball, or tennis. Most of the non-athletes also participated in athletic activities, but not on varsity teams. The research procedures were carried out with local IRB approval.

### 2.1 Spatial tasks

There were four spatial tasks that were completed outdoors and three that were completed in an immersive panoramic virtual environment (VR). These were followed by a computer-administered survey concerning knowledge of sport dimensions.

The outdoor tasks included, in order (1) verbal height estimation (for two poles, 4.9 m and 10.1 m high, tested in counterbalanced order from fixed distances equal to about one third the height of each pole); (2) verbal distance estimation to a sport cone in a level grass field

(distances of 2.5, 7.5, and 12.5 m, order counterbalanced); (3) visually directed, blindfolded walking to previewed targets at 5 m (as practice, with feedback only about walking speed if walking was abnormally slow) and 7.5 m; and (4) a single bean-bag toss to a target at 7.5 m (see Eby and Loomis 1987). For verbal estimation tasks, estimates were typically given in feet and inches, but five participants used meters. Participants were encouraged to be as precise as possible in their estimates.

The first task in the VR was a perceptual matching task in which the egocentric distance to a simulated metal pole (heights of 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20 m, presented in random order) was adjusted by moving the simulated pole until the egocentric distance to the pole appeared equal to the height of the pole (cf Li et al 2011). The scene was a simulated grassy field that extended to the horizon under a partly cloudy blue sky. The same scene was next used for verbal height estimation for poles of 5, 7.5, and 10 m viewed at varying viewing distances ranging from one-third of the pole height to 3 times the pole height. Additional filler trials of varying heights were also included. Finally, verbal estimates of distance were made to a simulated sport cone in the same simulated grassy field. The distances tested were 2.5, 5, 7.5, 10, 12.5, 15, 20, 25, and 30 m (in random order).

The computerized questionnaire surveyed participant knowledge about common sport dimensions in American sport, including the distance to first base in baseball, the height of the rim in basketball, the height of the goal posts in American football, the length of an Olympic swimming pool, the length of a regulation tennis court, and the typical length of an outdoor track. Information about current and past sport experience was also surveyed. Participants were also asked about any strategies they used for the various tasks.

## 2.2  Virtual environment apparatus

The virtual environment was experienced through a Sensics xSight head-mounted display with a 126° horizontal field of view (54° binocular overlap) and a 44° vertical field of view. The virtual environment was simulated at 60 Hz, through the use of Vizard. A HiBall 3000 optical head-tracking system provided low latency, high frequency updating. Observers made adjustments using a handheld wireless mouse and made verbal estimates orally, which were typed into the computer by a researcher who could not see the stimulus being presented.

## 3  Results

Due to technical problems the VR data of one athlete was lost. Extent estimates of one non-athlete in VR were also excluded from analysis because the majority were more than 4 standard deviations from the means of other participants. All other available data were used in each reported analysis.

## 3.1  Verbal distance estimation

Both in the outdoor environment and in VR, athletes tended to provide higher and more accurate distance estimates than did non-athletes. For example, the average estimate of the 12.5 m outdoor distance by athletes was 12.1 m (97%), which was reliably greater than the average estimate provided by non-athletes (9.9 m and 79%; $t_{48} = 2.08$, $p = 0.0425$). A multiple regression analysis including sex as a predictor along with being an athlete found reliable effects of both, but no interaction: Men's estimates (12.5 m) were reliably farther than women's (9.8 m) for the 12.5 m distance ($t_{46} = 2.73$, $p = 0.0090$), while athletes' estimates (12.1 m) were also reliably farther than those of non-athletes (9.9 m, $t_{46} = 2.27$, $p = 0.0280$). For the shorter outdoor distances, athletes and non-athletes provided very similar estimates, which were typically about 75% of the actual distance, as shown in Figure 2. Thus, it seemed that athletes were better calibrated only for the longer distance.

Distance perception in VR is known to be somewhat compressed relative to normal scenes (probably by a factor of about 0.8 in our set-up according to estimates of Li et
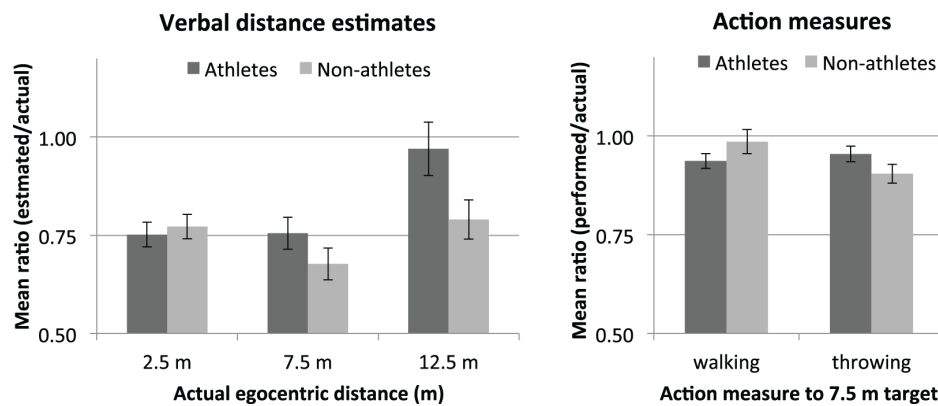
**Figure 2.** Egocentric distance estimation by verbal report (a) and by visually directed actions (b) for athletes and non-athletes. Standard errors of the means are shown.

al forthcoming), so we expected all participants to underestimate distances in VR, but for athletes to provide higher estimates than non-athletes. As shown in Figure 3, athletes provided distance estimates that tended to be consistently higher than those of non-athletes. The average gain of the athletes' judgments was 0.77. Taking VR compression into account (ie, dividing by 0.8), this suggests nearly perfect calibration (96%). In contrast, the average gain of the non-athletes was 0.56, consistent with underestimation, relative to athletes, by a factor of 0.72. Thus, the VR data seem roughly consistent with the outdoor data in suggesting that varsity athletes are much better calibrated than are the general population for estimating far distances. Separate $t$-tests ($\alpha = .02$) indicated that differences between the two groups were statistically reliable for presented distances of 10, 15, 25, and 30 m, replicating the outdoor observation that differences in calibration were more evident for farther distances. As in the outdoor data, for nearer distances athletes' estimates did not differ from those of non-athletes, and mean estimates for the 5 m and 7.5 m extents were reliably less than the expected compressed VR (0.8) values of 4 m ($M = 3.4$, $t_{46} = 3.15$, $p = 0.0029$) and 6 m ($M = 5.2$, $t_{46} = 2.49$, $p = 0.0164$), respectively.

### 3.2  Action measures of distance

The walking and throwing data are shown in the right panel of Figure 2. As expected, when the target was 7.5 m away, athletes ($M = 7.0$ m) were no differently calibrated than non-athletes (7.4 m) at visually-directed walking ($t_{48} = 1.41$, $p = 0.17$). Both groups were fairly accurate, though the overall walked distance (7.2 m) was reliably less than 7.5 m ($t_{48} = 2.30$, $p = 0.0259$). Athletes as a group were reliably less variable in their walking performance with a coefficient of variation (CoV: SD/M) of 10% compared to the non-athletes' CoV of 15% ($F_{22, 25} = 2.30$, $p = 0.0232$). A similar performance difference between athletes and non-athletes is evident in the data of Bredin et al (2005). Based on their report we have computed CoVs for their athletes (10%) and non-athletes (16%) when walking at normal speed, which are of the same magnitude as we found and also differ reliably from each other ($F_{19,20} = 2.59$, $p = 0.0204$). Thus, in spatial updating during open loop walking, athletes seem to consistently show less between-subject variability as a group in their performance.

Bean-bag throwing performance to a target at 7.5 m did not differ reliably between groups. Athletes ($M = 7.2$ m) did not throw the bean bag reliably more accurately than non-athletes ($M = 6.8$ m, $t_{48} = 1.6$, $p = 0.12$); nor did their respective CoV's (11% and 13%) differ reliably. The mean thrown distance (6.98 m) was reliably less than the 7.5 m target distance ($t_{48} = 4.42$, $p < 0.0001$). Note that participants had no practice tosses. There was no reliable correlation between thrown distance and walked distance within the athletes ($r = 0.24$, $t_{24} = 1.2$, $p = 0.24$), nor within the non-athletes ($r = -0.19$, $t_{21} = 0.88$, $p = 0.39$) suggesting that variability
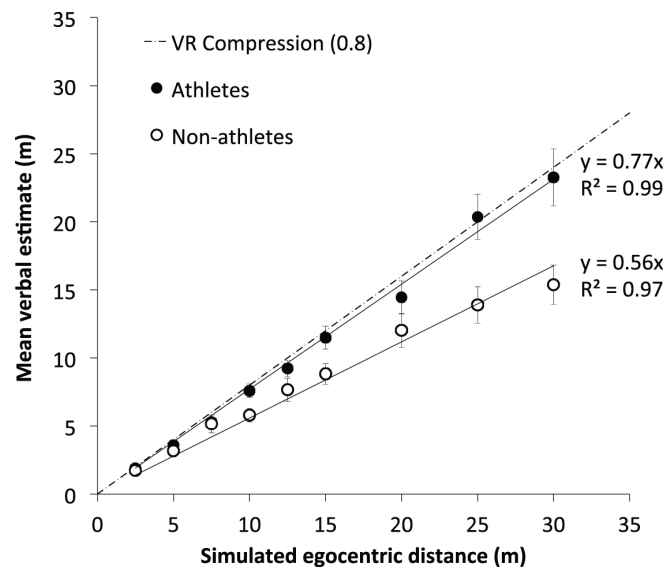
**Figure 3.** Egocentric distance estimation in VR for athletes and non-athletes. The dashed line represents expected VR distance compression. Filled circles represent the athletes' estimates. Open circles are the non-athletes' estimates. Standard errors of the means are shown. Note that error bars are smaller than plot points for short distances, which are underestimated by both groups relative to VR compression.

in the two measures is primarily due to variation in performance rather than in perception. Neither action measure was reliably correlated with participants' verbal estimates of the 7.5 m distance, either, with $r$'s ranging from –0.12 (athletes' verbal estimates and throws) to 0.26 (non-athletes' verbal estimates and throws).

Verbal estimates of distance were much more variable between subjects than were action measures. Between-subject CoVs ranged from 19% to 37% both for verbal distance and height estimation, with the largest CoVs being among athletes for the 12.5 m distance (36%) and the 10.1 m height (37%). Non-athletes also showed a great deal of between-subject variability in their height estimates of the taller pole (CoV = 34%).

## 3.3 Verbal height estimation

A 2 (tall versus short pole: within subjects) x 2 (athlete versus non-athlete: between subjects) mixed ANOVA found that athletes and non-athletes did not differ reliably in their estimates of pole height outdoors ($F_{1, 47} < 1$). Overall height estimates did not differ from actual height for either the 10.1 m pole ($M = 10.2$ m; 95% CI 9.1 – 11.2 m, $t_{48} = 0.12$, *ns*), or the 4.9 m pole ($M = 5.0$; 95% CI 4.6 – 5.4 m, $t_{48} = 0.52$, *ns*). Most participants (57%; 12 athletes, 16 non-athletes) reported using a human height or eye-level strategy such as imagining a person of 5 or 6 feet (1.5 or 1.8 m) up against the pole and counting out intervals of 5 or 6 feet. Thus, although some athletes reported using sports knowledge (eg, the height of a basketball rim, $N = 5$) as a reference, human height information evidently represents an area of general expertise that all participants could use for the heights we tested.

In VR, height estimates did not differ reliably by viewing distance, and estimates were therefore averaged across viewing distance. The resulting height estimates did not differ between athletes and non-athletes for the 5 m ($M = 4.1$ m; 0.83) or 7.5 m ($M = 6.4$ m; 0.85) poles, and athletes' estimates for the 10 m pole ($M = 9.1$; 0.91) were only marginally larger than non-athlete estimates ($M = 7.8$; 0.78, $t_{46} = 1.82$, $p = 0.0718$). The overall mean for the 10 m pole ($M = 8.5$ m; 0.85) was in the same proportion as the means for the shorter poles. Assuming VR size compression by about 0.8, verbal height estimates in VR were consistent with the fairly accurate verbal height estimates outdoors.

### 3.4 Egocentric distance matching to vertical extents

The perceptual matching data are shown for athletes and non-athletes in Figure 4. Given that athletes and non-athletes do not differ in their verbal estimates of height, but differ reliably in the verbal estimates of distance, it might be predicted that athletes would show a different matching function than non-athletes. Indeed, given that athletes provide higher estimates of distance, their egocentric distance matches should be less than those of non-athletes, but the trend is in the wrong direction and is not reliable according to a mixed-effects model of produced distance as a function of pole height and athletic status ($t_{379} = 1.54$, $p = 0.12$). In other words, athletes' perceptual matches between height and egocentric distances do not seem to be altered as a result of their skill at distance estimation.

Between-subject variability was also similar in the two groups. Between-subject CoVs computed for each group at each pole height averaged 23% for athletes and 25% for non-athletes.
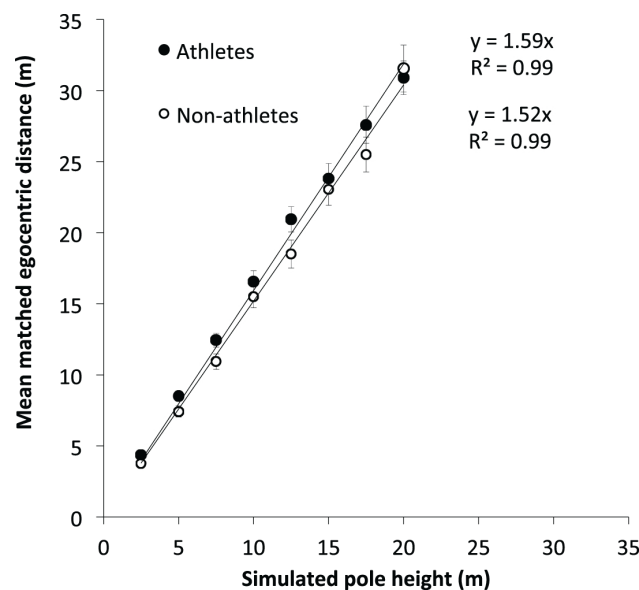


**Figure 4.** Egocentric distance matches to vertical extents in VR for athletes and non-athletes. Filled circles represent the athletes' matches. Open circles are the non-athletes' matches. Standard errors of the means are shown.

### 3.5 Test of correspondence between perceptual matching and estimation

Do the perceptual matches of the athletes or of the non-athletes correspond to their verbal estimates? That is, for a given match point between a vertical extent and an egocentric ground extent, it might be expected that verbal estimates associated with each of the two matched extents would not differ. In particular, if athletes' verbal estimates of distance and height corresponded to their relative perceptions as assessed by their distance/height matching performance, it should be possible to predict their verbal estimates of a specific egocentric distance (eg, the distance matched to the 10 m virtual pole) based on their verbal estimates of the 10 m virtual pole. The average verbal estimate for the 10 m virtual pole among athletes was 9.1 m, while their average matching distance for the 10 m pole was 16.7 m. What verbal estimate would athletes have given for a 16.7 m egocentric distance?

A linear regression line fit to each participant's VR distance estimation data was used to compute the verbal estimate corresponding to the egocentric matching distance they had produced for the 10 m-high pole. These estimates ($M = 12.5$ m) were reliably higher for athletes than their estimates for the 10 m pole ($M = 9.1$ m, $t_{24} = 4.29$, $p = 0.0003$). This

indicates that the matching task was not accomplished by comparing verbal estimates and therefore does not reflect cognitive calibration of egocentric distance evident in athletes' explicit verbal estimates. In contrast, for non-athletes, the inferred verbal distance estimates for their egocentric matches to the 10 m pole ($M = 8.6$) did not differ reliably from their verbal estimates of the 10 m pole itself ($M = 7.8$ m, $t_{21} = 1.39$, $p = 0.18$). That is, for non-athletes there is a correspondence between perceptual matching and estimation. Thus, our data suggest that the verbal estimates of non-athletes correspond more closely to their relative perceptions of height and distance than do the verbal estimates of athletes. Although athletes were more accurate than non-athletes at distance estimation, their verbal estimates probably reflect cognitive calibration that allowed them to more accurately estimate distances. This cognitive calibration does not seem to have altered their perceptual experience of those distances as measured by the matching task.

## 3.6  Sport dimensions knowledge

**Table 1.** Survey estimates of standard sport dimensions ($M \pm$ SD).

| Sport dimension | Magnitude | Athletes | Non-athletes | $p$-value[a] |
|---|---|---|---|---|
| American Football Uprights | 12.20 m | 9.16 ± 9.28 | 9.45 ± 8.23 | 0.9177 |
| Basketball Rim Height | 3.05 m | 3.09[b] ± 0.19 | 3.88[b] ± 1.96 | 0.0468 |
| Distance to First Base | 27.40 m | 22.10[b] ± 8.40 | 13.3 ± 6.9 | 0.0009 |
| Olympic Pool Length | 50.00 m | 76.80[b] ± 84.50 | 98.8[b] ± 129.00 | 0.6692 |
| Outdoor Track Length | 400.00 m | 399.00[b] ± 7.00[c] | 448.00[b] ± 321.00 | 0.4365 |
| Tennis Court Length | 23.40 m | 26.50 ± 11.30 | 19.2 ± 12.6 | 0.0537 |

[a] Results of $t$-tests comparing athletes and non-athletes. Not all participants provided estimates for all dimensions, but $N$ is always at least 41 per pair and 18 per cell.
[b] The median estimate was accurate.
[c] Variance here is due to estimates using non-metric units (eg, "1300 feet").

As expected, athletes were far more likely to correctly answer questions about sport dimensions than were non-athletes. Mean estimates are shown in Table 1. Although only one athlete was a varsity baseball player, 54% (14) of our athletes knew the distance to first base compared to 4% (1) of our non-athletes ($\chi^2_1 = 11.8$, $p = 0.0006$). Although fewer than half of our athletes played varsity basketball, 85% (22) knew the height of the basketball rim, compared to 22% (5) of our non-athletes ($\chi^2_1 = 17.0$, $p < 0.0001$). All of our athletes (26) knew the length of the track, but only 52% (12) of our non-athletes knew it ($\chi^2_1 = 13.4$, $p = 0.0003$). The remaining questions (tennis court, Olympic pool, American football uprights) were answered correctly by fewer than half of either group and did not reliably discriminate between athletes and non-athletes, though, consistent with cognitive correction, athletes tended to give longer estimates for ground distances (ie, a tennis court) than did non-athletes, as shown in Table 1. Overall, athletes appeared to know a great deal about standard distances that might be useful when making estimates of distance on grass. Although non-athletes were less likely to be familiar with sport dimensions, height estimation can be calibrated by knowledge of human heights.

## 4  Discussion

It is widely understood that the use of verbal estimation techniques is susceptible to cognitive and social biases. In the present instance we thought it useful to document a striking difference (and two striking similarities) between college athletes and other college students. Presumably because of their familiarity with known sport dimensions, varsity athletes showed much better calibration of their verbal distance estimates than did non-athletes. Height

estimation was well-calibrated for both groups. Despite their greater cognitive calibration of far distances, however, when athletes were asked to match perceived egocentric distances to perceived heights, they showed the same systematic biases that non-athletes show.

Although the present matching task was conducted in a virtual environment, it was the same virtual environment used to collect the VR height and distance estimates for which comparisons were made. Moreover, Li et al (2011) found exactly the same pattern of perceptual matching data both in VR and in an outdoor environment, and Higashiyama and Ueyama (1988) found the same pattern of behavior in outdoor environments. The advantage of using VR for the matching task is that it allows one to vary starting positions randomly and to quickly collect precise distance-matching data for a wide range of pole heights. Given the separation in the VR distance estimates between athletes and non-athletes, the absence of any difference in the matching task is strong evidence that the improved scaling of verbal distance estimation in athletes is cognitive rather than perceptual.

There is surprisingly little data on verbal height estimation for vertical extents observed frontally. Studies of vertical extents viewed approximately along the line of sight (ie, looking up or looking down) tend to be exaggerated (Kammann 1967), especially when looking down (Jackson and Cormack 2007; Stefanucci and Proffitt 2009). Our verbal estimation data suggest a surprising level of accuracy for estimates of pole heights viewed frontally. However, the self-reported strategy of the majority of our participants seems to involve a kind of common knowledge (general expertise) of human heights. Such knowledge can form the basis for good cognitive calibration for height judgments. For our non-athletes, egocentric distance estimates were scaled in a manner that was roughly consistent with their height estimates combined with their perceptual matches of egocentric distances to heights. This suggests that human height may indeed be a ruler that provides a crude basis for verbal estimates of egocentric distance as well, in the absence of known points of reference such as the dimensions of athletic fields.

For near distances (less than 10 m), athletes and non-athletes in our sample underestimated distance in both environments tested and did not differ from each other reliably in their egocentric distance estimates, but for farther distances there were clear differences between the two groups. Athletes were much more accurate. The difference seems likely to be due to familiarity with points of reference for judging distance (many different points of reference could serve this purpose) which are, as a class, more widely known among varsity athletes. Some athletes referred specifically to known distances such as the distance for a penalty kick (11 m) when describing their strategies. Knowledge of these points of reference did not alter performance on a perceptual matching task in which no explicit estimates were required. Calibration also did not extend to near space, which may signal that athletes are not aware of the perceptual bias in near space, and have only learned to correct for it with farther points of reference. We therefore tentatively conclude that athletes' perception of space is not scaled differently than that of non-athletes, even though their explicit judgments of far space are better calibrated.

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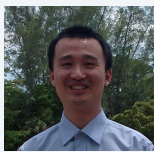
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