Acta Psychologica 157 (2015) 74–84

Contents lists available at ScienceDirect

Acta Psychologica

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

Mapping the structure of perceptual and visual–motor abilities in healthy young adults

Lingling Wang [a,b], Kristina Krasich [a,b], Tarik Bel-Bahar [a], Lauren Hughes [a], Stephen R. Mitroff [b,c], L. Gregory Appelbaum [a,b,*]

[a] Department of Psychiatry and Behavioral Science, Duke Medical Center, Durham, NC, USA
[b] Center for Cognitive Neuroscience, Duke University, Durham, NC, USA
[c] Department of Psychology & Neuroscience, Duke University, Durham, NC, USA

ARTICLE INFO

Article history:
Received 27 August 2014
Received in revised form 5 February 2015
Accepted 10 February 2015
Available online xxxx

Keywords:
2221 Sensory & Motor Testing
2320 Sensory Perception
2330 Motor Processes

ABSTRACT

The ability to quickly detect and respond to visual stimuli in the environment is critical to many human activities. While such perceptual and visual–motor skills are important in a myriad of contexts, considerable variability exists between individuals in these abilities. To better understand the sources of this variability, we assessed perceptual and visual–motor skills in a large sample of 230 healthy individuals via the Nike SPARQ Sensory Station, and compared variability in their behavioral performance to demographic, state, sleep and consumption characteristics. Dimension reduction and regression analyses indicated three underlying factors: Visual–Motor Control, Visual Sensitivity, and Eye Quickness, which accounted for roughly half of the overall population variance in performance on this battery. Inter-individual variability in Visual–Motor Control was correlated with gender and circadian patters such that performance on this factor was better for males and for those who had been awake for a longer period of time before assessment. The current findings indicate that abilities involving coordinated hand movements in response to stimuli are subject to greater individual variability, while visual sensitivity and occulomotor control are largely stable across individuals.

1. Introduction

Success in many human endeavors requires individuals to efficiently process visual information to generate swift and appropriate motor actions. Whether driving a car, playing sports, or walking around town, people must be able to see what is around them, direct their attention to the most relevant information, and orient their bodies to successfully react to the changing environment. Despite the importance of these perceptual and visual–motor abilities, there is considerable variability between individuals in their capacity to see and react. In fact, inter-individual variability in sensory-guided motor behavior abilities has been utilized across a great number of studies aimed at understanding what factors contribute to greater or lesser achievement in different applied settings. The results of these studies indicate that better perceptual and visual–motor skills are predictive of success in a number of important endeavors, including industrial job performance (Hunter, 1986; Hunter & Hunter, 1984), military duties (Griffin & Koonce, 1996; Johnston & Catano, 2002; King et al., 2013), and surgical performance (Datta et al., 2002; Maan, Maan, Darzi, & Aggarwal, 2012). In a similar vein, two recent meta reviews of the sports expertise literature demonstrate that certain visual–perceptual abilities are enhanced in more accomplished athletes, relative to less accomplished athletes (Mann, Williams, Ward, & Janelle, 2007; Voss, Kramer, Basak, Prakash, & Roberts, 2010). Taken together, these studies indicate the need for proficient visual and motor skills and the presence of considerable variability in these skills across the population. Thus, the aim of the current study is to better understand the sources of this inter-individual variability across a small set of demographic and state characteristics in a sample of healthy young adults.

1.1. Measuring perceptual and visual–motor skills

Given the importance of perceptual and visual–motor skills and the literature showing that they are predictive of success in applied pursuits, there is a growing movement towards developing tools to assess and train these abilities. Among these tools is the Nike SPARQ Sensory Station (Nike, Inc., Beaverton, Oregon), a computerized assessment device equipped with a battery of nine psychometric tasks that are administered with video instructions in about 30 min by certified trainers. The interactive tasks are measures of Static Visual Acuity, Contrast Sensitivity, Depth Perception, Near-Far Quickness, Dynamic Visual Acuity, Perception Span, Eye–Hand Coordination, Go/No-Go and Hand Response Time that have previously been identified as important abilities for sports (Erickson, 2012; Hitzeman & Beckerman, 1993). This

* Corresponding author at: Duke University Hospital, 400 Trent Dr., Durham, NC 27710, USA. Tel.: +1 919 613 7664; fax: +1 919 681 8744.
E-mail address: greg@duke.edu (L.G. Appelbaum).

http://dx.doi.org/10.1016/j.actpsy.2015.02.005
0001-6918/

battery includes information about the participant (e.g. age, gender, height, sport, level, position, concussion history), followed by a series of behavioral tasks that are arranged hierarchically so that stimuli presented later in the battery are scaled according to sensitivity thresholds measured in early tasks.

The Sensory Station devices have been deployed in a number of athletic, clinical, and military training facilities (http://www.ssusersgroup.weebly.com), and offer a broad platform from which to study perceptual and visual–motor skills in applied contexts. Test–retest reliability on the Sensory Station has been replicated in two samples (Erickson et al., 2011; Gilrein, 2014), both of which demonstrated stable test–retest performance on assessments of Static Visual Acuity, Contrast Sensitivity, Depth Perception, Dynamic Visual Acuity, and Hand Response Time, while moderate re-test improvements were found for the Near–Far Quickness, Perception Span, Eye–Hand Coordination, and Go/No-Go measures. Moreover, when measured over 10 successive sessions, learning in these tasks was principally linear with as much as 60% improvement in some tasks (Krasich et al., under review). Recent studies have also begun to establish a direct external validity between the Sensory Station battery and real-world performance. For example, using logistic regression techniques, it was shown that better performance on the Perception Span, Near–Far Quickness, Go/No-Go and Hand Reaction Time tasks accounted for 69% of the variability in goals scored over two seasons in a sample of 42 collegiate hockey players (Poltavski & Biberdorff, 2014). Additionally, in comparing overall performance on the Sensory Station battery among 38 men's varsity football players, worse overall scores were associated with an increased likelihood of sustaining severe head impacts during practices and games, indicating a link between collision avoidance and perceptual and visual–motor skills (Harpham, Mihalik, Littleton, Frank, & Guskiewicz, 2014). Together, these studies suggest that the perceptual and visual–motor abilities measured by the Sensory Station are related to important performance outcomes, and further indicate the need to understand how variability in these skills is expressed across individuals.

1.2. Factors influencing perceptual and visual–motor performance

Performance on perceptual and visual–motor tasks can be greatly affected by a number of individual-difference characteristics. Gender differences, specifically, have been demonstrated in many studies, with males demonstrating faster motor speeds (Kauranen & Vanharanta, 1996; Ruff & Parker, 1993; Thomas & French, 1985), better eye–hand coordination, and better visual–spatial abilities (Ruff & Parker, 1993; Thomas & French, 1985; Voyer, Voyer, & Bryden, 1995), whereas females exhibit faster perceptual processing speeds and greater verbal fluency (e.g., Halpern, Straight, & Stephenson, 2011; Kimura 1999; Voyer et al., 1995). These well-documented gender differences in various psychomotor and cognitive abilities provide an initial expectation that gender differences may be observed in the perceptual and visual–motor tasks.

In addition to gender differences, research has also shown that perceptual and visual–motor performance can be substantially modulated by an individual's psychological state. For example, current stress and anxiety levels are often negatively correlated with cognitive and motor performance (e.g., Bolmont, Gangloff, Vouriot, & Perrin, 2002; Han et al., 2011; Raglin, 1992). Past research has also highlighted the role of affect state in modulating task performance, with higher positive state affect and lower negative state affect being associated with better cognitive (Fredrickson & Branigan, 2005; Muraven & Baumeister, 2000), athletic (Skinner & Brewer, 2004), and work performance (Kaplan, Bradley, Luchman, & Haynes, 2009; Wright, Cropanzano, & Meyer, 2004). Specifically, positive emotions have been shown to facilitate effective competition preparation, and benefit subsequent performance (Skinner & Brewer, 2002, 2004). Therefore, participants' stress level and affective state should also been taken into account when assessing individual differences in perceptual and visual–motor performance.

Finally, previous research has shown that circadian rhythm, and specifically the sleep–wake cycle, is another important factor that influences individual performance on sensory, motor, reaction time, time estimation, and memory tasks (Carrier & Monk, 2000, for a review; Matchock & Mordkoff, 2007; Breimhorst, Falkenstein, Marks, & Griefahn, 2008; Jarraya, Jarraya, Chtourou, Souissi, & Chamari, 2013). In healthy adults who typically sleep from 23:00 to 7:00, peak cognitive performance is often observed during 16:00–22:00 while the lowest levels of performance are reported between 7:00 and 10:00 (Matchock, 2010; Valdez, Ramírez, & García, 2012); however, caffeine and food consumption can alter normal biological rhythms (Valdez et al., 2012).

1.3. The current study

In light of the associations described above, the present study sought to investigate inter-individual variability in perceptual and visual–motor abilities by measuring behavioral performance on the Sensory Station battery, and relating variability in this performance to gender, psychological state, sleep, and consumption history for each of the 230 healthy college-aged participants. For this purpose, the individual Sensory Station measures were submitted to dimension reduction analyses to identify latent factors that underlie perceptual and visual–motor abilities, and then regression analyses were performed on each of the identified latent factors to determine the influence of those individual-difference characteristics. By quantifying performance in these important visual and motor skills, and their relationship to a small set of individual-difference characteristics, the present study provides a platform for understanding how variability in perceptual and visual–motor abilities can affect human performance.

2. Method

2.1. Participants

Two hundred and thirty individuals (105 males, 125 females) completed in a series of assessments across multiple testing sessions as part of a larger research endeavor conducted in the Perception Performance and Psychophysiology Lab at the Duke University Medical Center. The participants ranged in age from 18 to 24 years (Mean = 20.5, SD = 1.6), and were not current or former collegiate varsity athletes. They were compensated $20/h and voluntarily participated under an experimental protocol approved by Duke University's Institutional Review Board. All participants completed a general protocol that included at least two types of assessments: psychophysical measurement of visual and visual–motor abilities assessed by the Nike SPARQ Sensory Station, and self-report questionnaires about their psychological state, recent sleep/circadian rhythm, and consumption history.

2.2. Psychophysical measures

2.2.1. Nike SPARQ Sensory Station

Psychophysical measures were performed on the Nike SPARQ Sensory Station (Nike Inc., Beaverton OR). The Sensory Station battery consists of nine computerized tasks; four of the nine tasks measure visual sensitivity thresholds and the other five tasks assess visual and visual–motor abilities. Brief descriptions for each task are included below, and schematic illustrations are displayed in Fig. 1. More detailed reports of task procedures are included in Erickson et al. (2011) and Poltavski and Biberdorff (2014).

2.2.1.1. Staircase visual sensitivity tasks. The four tasks measuring visual sensitivity – Static Visual Acuity, Dynamic Visual Acuity, Contrast Sensitivity and Depth Perception – were presented on a 23-inch display monitor, with participants standing 16 ft (4.9 m) away from the Station and responding via a handheld Apple iPod touch® (Apple Inc., Cupertino,

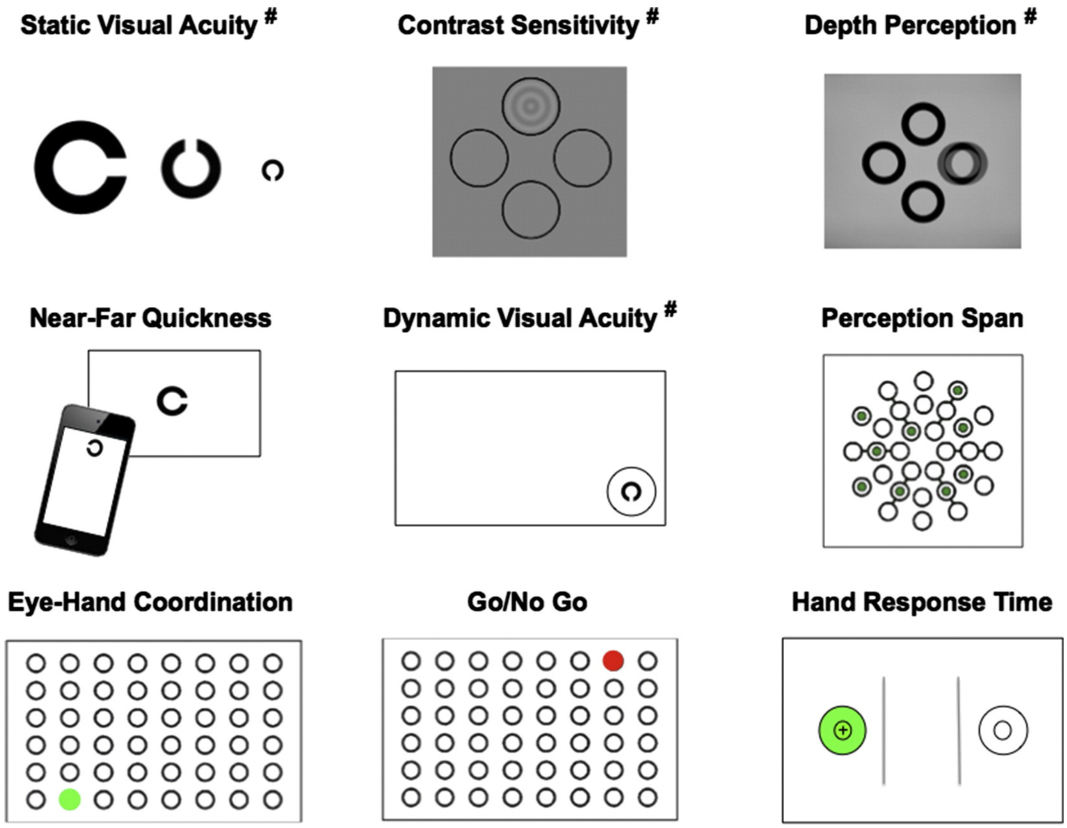

Fig. 1. Sensory Station task battery. Illustrations of the nine perceptual and visual–motor tasks included in the Nike SPARQ Sensory Station battery. # indicates tasks that performed under a staircase schedule.

CA) that was wirelessly connected to the Station computer. Stimulus presentation and final thresholds were determined on a staircase procedure, wherein the difficulty level of the presented stimuli was dynamically adjusted in accordance with the performance of the participant. From an initial pre-set starting level (depending on the task), the stimulus was presented at a more difficult level following each correct response, while an easier level followed each incorrect response. The staircase ended once two adjacent levels each recorded two correct and two incorrect responses. The highest level with two correct responses was defined as the sensitivity threshold for that task.

The *Static Visual Acuity (SVA)* task assessed the minimum detectable spatial resolution for a non-moving object. In this task, a black Landolt ring with a gap was presented on a white background in the center of the screen. The gap could be at the top, bottom, left, or right of the ring, and participants were asked to swipe the screen of the iPod in the direction of the gap. The resolution of the gap started equivalent to 20/50 Snellen acuity, and was adjusted following the staircase procedures described above. Right monocular, left monocular and binocular acuities were measured in a fixed order. Static Visual Acuity thresholds were transformed to LogMAR units, wherein a value of 0 indicates normal visual acuity (i.e., 20/20 vision), with negative values indicating better than normal visual acuity, and positive values denoting worse visual acuity.

The *Contrast Sensitivity (CS)* task assessed the minimum contrast level to distinguish lightness and darkness. Four black circles were presented in a diamond configuration on a light gray background, with one of the circles randomly containing a pattern of concentric rings. Participants were asked to swipe in the direction of the circle with the pattern. Stimuli were adjusted following the staircase procedure described above. Contrast Sensitivity was measured binocularly at 6 and 18 cycles per degree (cpd), and log transformed, with larger values indicating better Contrast Sensitivity.

The *Depth Perception (DP)* task assessed the smallest amount of disparity required to resolve differences in depth. Four black rings were presented in a diamond configuration on a light gray background. Participants wore a pair of liquid crystal goggles (NVIDIA 3D Vision, Santa Clara, California) that creates simulated depth in one of the four rings. Participants were asked to swipe on the iPod in the direction of the ring that appeared to have depth. This task was conducted under three viewing conditions in a fixed order: facing front, facing left and looking over the right shoulder, and facing right and looking over the left shoulder. The Depth Perception threshold was measured following the staircase procedure described above, ranging between 237 and 12 arc. In addition to measuring disparity thresholds, this task also measured response speed by encouraging participants to respond as quickly as possible. Response times for each viewing condition were computed by averaging across all but the first trial.

The *Dynamic Visual Acuity (DVA)* task assessed the ability to resolve a brief, peripherally presented target. A black Landolt ring (0.1 log unit above SVA threshold) was presented on one of the four corners of the 42-inch screen. The presentation duration of the Landolt ring started at 250 ms and was dynamically adjusted following the staircase procedures explained above. Participants were asked to identify the direction of the gap on the Landolt ring by swiping on the iPod screen. Final Dynamic Visual Acuity thresholds were the minimum amount of presentation time in milliseconds required to correctly identify the gap in the ring, with shorter durations indicating better Dynamic Visual Acuity.

2.2.1.2. Psychomotor tasks. Among the psychomotor tasks, four of the five tasks – Perception Span, Eye–Hand Coordination, Go/No-Go, and Hand Response Time – were conducted on the 42-inch touch sensitive screen positioned eye-level and arm's length from the participant. The fifth task, Near–Far Quickness, presented stimuli on the 23-inch screen with participants standing 16 ft away and responding via the iPod. These five tasks did not use a staircase procedure.

Near-Far Quickness (NFQ) measured how quickly and accurately participants could visually accommodate between near and far targets. During this task, a black Landolt ring was alternatingly presented in the center of the 'far' 23-inch screen of the Station and at the top of the 'near' screen of the handheld iPod. Participants were asked to swipe the iPod screen to indicate the direction of the gap as quickly as possible. The next stimulus appeared on the successive screen only after a correct response was registered for the current stimulus. Near–Far Quickness scores were the total number of correct responses made in 30-s.

The *Perception Span (PS)* task assessed spatial working memory for briefly presented patterns of dots. During this task, a grid of white circles in a radial configuration was displayed on the large 42-inch touch screen. For each trial, a subset of the circles was briefly filled with green dots, and participants were asked to recreate the pattern of the flashed green dots by touching the corresponding circles. There are 11 levels in total that the participant could possibly achieve, with increased size of the grid and more complex spatial patterns of the green dots occurring at each successive level. The task ended when participants could no longer reach a passing score (100% correct for the first three levels and 75% correct for the higher levels) on two successive trials for a given level. PS scores were computed as the total number of correctly identified dots minus the number of missed or falsely identified dots across all of the trials.

Eye–Hand Coordination (EHC) measured the ability to quickly and accurately touch a sequence of briefly presented targets. A grid consisting of 48 (8 columns × 6 rows) equally spaced black circles was presented on the screen. During the task, a green dot appeared in each of the circles twice in a pseudo-random order. Participants were asked to touch the dot as rapidly as possible using either hand. As soon as the dot was touched, it was presented at a new location. This would continue until a sequence of 96 presented dots was successfully completed (two at each of the 48 locations). The score for Eye–Hand Coordination was the total time it took to complete the sequence.

The *Go/No-Go (GNG)* task tested the ability to rapidly respond to "go" targets while inhibiting responses to "no-go" non-targets. This task was similar to Eye–Hand Coordination except that the dots were presented for only 500 ms and could be either green or red. Participants were instructed to touch the green dots as quickly as possible, but to withhold responses to the red dots. Ninety-six total dots (64 green, 32 red) were presented in a pseudo-randomized sequence. Final Go/No-Go scores were computed as the total number of green dots successfully touched within the 500 ms window minus the number of red dots incorrectly touched.

The *Response Time (RSP)* task measured simple motor reaction time in response to a visual stimulus. During this task, two rings were presented on either side of the 42-inch touch screen. Participants were asked to place the fingertips of their dominant hand in the 'starting' ring on that side of their body, while aligning their body with the other 'landing' ring. Once the landing ring turned green, participant disengaged from the starting ring and made a ballistic hand movement to touch the landing ring as quickly and accurately as possible. Participants would complete seven trials, with the possibility to repeat up to two of these trials if they were slower than two standard deviations from the mean. Response Time was computed as the average time it took to disengage from the starting ring and engage with the landing ring for the seven trials.

2.2.2. Additional visual assessments

Additional measures of visual sensitivity were collected to provide independent assessments and cross-validate thresholds measured by the Sensory Station. Prior to the Sensory Station tasks, visual acuity was measured with a standard Snellen Eye Chart on a subset of participants (binocular only, $N = 157$; both monocular and binocular, $N = 133$). Participants stood at a distance of 20 ft from the chart and visual acuity was determined as the smallest line of letters where the participant could report 50% accuracy under monocular left eye, monocular right eye, and binocular viewing conditions. Following the completion of the Sensory Station assessments, full Contrast Sensitivity functions were measured on 108 participants using the Quick Contrast Sensitivity Function Test (QuickCSF; Adaptive Sensory Technology, Boston MA). The QuickCSF Test was implemented on a pixel-calibrated 4th generation iPad® (Apple Inc., Cupertino, CA), and measured the Contrast Sensitivity on a wide frequency range from 0.1 to 30 cpd (Dorr, Lesmes, Lu, & Bex, 2013). Threshold estimates were computed at 6 and 18 cpd for comparison to the performance on the Sensory Station.

2.3. Self-report questionnaires

All participants completed a series of self-report questionnaires aimed at assessing their current psychological state, recent history of consumption, and recent sleep activities. These questionnaires were administered using web-based survey software on an iPad prior to the start of the psychophysical assessments.

2.3.1. Current psychological state

The self-reported level of currently perceived anxiety was assessed using the 20-item State-Trait Anxiety Inventory (STAI, Spielberger, Gorsuch, & Lushene, 1970), with "current moment" instructions ("indicate how you feel right now, that is, at this moment"). Responses were given on a 4-point Likert scale ranging from 1 = *Not at all* to 4 = *Very much so*. The STAI has high internal reliability ($\alpha s > 0.89$), as well as convergent and discriminant validity with other measures of anxiety (Barnes, Harp, & Jung, 2002; Spielberger, 2010). Self-reported current state affect was assessed by the Positive and Negative Affect Schedule (PANAS, Watson & Clark, 1999; 20-item version) with "current moment" instructions. Responses were given from 1 = *very slightly, not at all* to 5 = *extremely*. The PANAS has high internal reliability ($\alpha = 0.72$ to 0.89), test–retest reliability (from $r = 0.58$ to 0.72), and convergent validity with other measures of state affect (Leue, A., & Beauducel, A. (2011); Watson & Clark, 1999).

2.3.2. Recent history of consumption

Participants reported their recent consumption of caffeine through two questions: 1) When was the last time you drank a cup of coffee? 2) When was the last time you drank a caffeinated or sugary drink that was not coffee, such as tea or soda? Responses were given on an 8-point Likert scale: 0 = *I do not drink coffee (caffeinated drinks)*, 1 = *Less than 30 min ago*, 2 = *30 min to 1 h ago*, 3 = *1 to 3 h ago*, 4 = *3 to 6 h ago*, 5 = *6 to 12 h ago*, 6 = *12 to 24 h ago*, and 7 = *More than 24 h ago*. Participants also reported their recent food consumption through two questions using the same Likert scale: 1) When was the last time you had a meal? 2) When was the last time you had anything to eat (including small snacks or candy)? For analysis purposes, history values were taken as the more recent of the two caffeine questions and the more recent of the two food questions. These scores were used as nominal variables in the linear regression analyses.

2.3.3. Sleep metrics

Using a 30-minute interval scale, participants reported the time at which they went to sleep the previous evening, and the time at which they awoke in the morning. Total sleep time was computed as the difference between these values. In addition, the total time that they had been awake that day prior to their assessment (Time Awake) was computed as the difference in minutes between the session start time and the reported awakening time that morning. The range of Time Awake was between 30 min and 690 min in our sample, and was used as a scalar variable in the linear regression analyses. It should be noted that the time of testing correlated highly with Time Awake ($r = .82$), and therefore only Time Awake was used in the regression model.

2.4. Analyses

2.4.1. Data preprocessing

Data were preprocessed to replace missing values and eliminate outlier responses. Among the 230 participants tested on the Sensory Station, data were missing for six participants on the Response Time task due to a technical error that occurred when exiting the assessment. These data values were replaced with the population mean. Among the seven self-report variables (excluding gender, which had no missing cases), roughly 7% of the questionnaires had missing values. These cases were imputed using the SPSS missing values toolbox. In addition, one Sleep Time response and one Negative Affect response fell greater than 3 standard deviations beyond their respective variable mean, and these two were removed as outliers. For those individual Sensory Station tasks with multiple conditions, one-way ANOVAs with Bonferroni correction were used to compare the individual condition differences.

2.4.2. Dimension reduction

Exploratory factor analysis is a well-established approach for reducing the dimensionality of a large dataset in order to identify latent structures between variables that might otherwise be hidden. Principal-axis factoring (PFA) is one such dimension reduction approach that does not rely on the assumption of normalcy (Fabrigar et al., 1999). As the performance did not adhere to normal distributions on all tasks (see Supplemental material 1), it was deemed that PFA was the optimal factor approach for the current study. Therefore, PFA factor analysis was performed on the final set of ten individual Sensory Station measures derived from the first phase analysis (nine tasks with both thresholds and response times from the Depth Perception task). The decision to retain three extracted factors was determined by a combination of scree test (a clear inflection point in the plot) and eigenvalue scores (a clear gap in scores between 3 and 4). Finally, the retained factors were varimax rotated (Wood, Tataryn, & Gorsuch, 1996) to minimize the complexity of the factors and to optimally identify each variable with a single factor. Factor loadings for each participant were derived using the regression method and submitted to subsequent independent samples *t*-test and correlational analyses. These analyses were conducted using SPSS 18.0.

3. Results

Three aspects of the experimental results are presented below. First, the results from each of the tasks in the Sensory Station battery are described. For each of these tasks, the motivation for using specific variables in the second-stage factor analyses is presented, and where available, these results are cross-validated with independent assessment measures. Second, the results of the between-task analyses describing the latent factors that underlie perceptual and visual–motor performance across the current sample are presented. Finally, behavioral performance on the battery is related to individual differences in gender, psychological state, sleep, and consumption history to explore how perceptual and visual–motor abilities vary across these characteristics.

3.1. Sensory station task results

3.1.1. Static Visual Acuity (SVA)

Static Visual Acuity was measured under three viewing conditions using both the Sensory Station Static Visual Acuity task, and for cross validation, a standard Snellen Eye Chart. A one-way ANOVA revealed a significant difference across the three viewing conditions $F = 23.52$ $(2, 689)$, $p < 0.001$. Binocular Static Visual Acuity was better than left ($p < 0.001$) and right monocular Static Visual Acuity ($p < 0.001$), with no difference between left and right monocular Static Visual Acuity ($p = 1$). Static Visual Acuity threshold correlated across all three viewing conditions (all r's > 0.34, p's < 0.001).

Static Visual Acuity as measured by the Snellen Eye Chart produced the same pattern of results, wherein significant differences were observed between the three viewing conditions $F = 13.59$ $(2, 422)$, $p < 0.001$, with binocular Static Visual Acuity showing lower thresholds than left ($p < 0.001$) and right monocular Static Visual Acuity ($p < 0.001$), and no difference between left and right monocular Static Visual Acuity ($p = 1$). It is important to note that Static Visual Acuity was significantly correlated between the two assessments for each of the three viewing conditions (all r's > 0.40, p's < 0.001), and the absolute differences between the two assessments was rather small (left Δ 0.015; right Δ 0.007; binocular Δ 0.028), indicating the external validity of the Sensory Station measure. To minimize potential sampling error imposed by the individual staircase functions for each of the three viewing conditions, the three-condition average was used as the measure of interest for the second-stage factor analysis described in the following sections.

3.1.2. Contrast Sensitivity (CS)

Contrast Sensitivity was measured at 6 and 18 cpd using the Sensory Station, and as a continuous spatial frequency function using the QuickCSF Task (Lesmes, Lu, Baek, & Albright, 2010) in 108 of the participants. Consistent with the literature (e.g., Hashemi et al., 2012; Robson, 1966), Contrast Sensitivity measured by the Sensory Station was significantly better at 6 cpd than at 18 cpd, ($t(229) = 35.289$, $p < 0.001$). It should be noted, however, that for 43% of participants, performance reached the ceiling of stimulus contrasts levels available at the 6 cpd condition (maximum value = 2.4) on the Sensory Station Contrast Sensitivity assessment. Because of this, Contrast Sensitivity may be underestimated for this viewing condition. Nonetheless, Contrast Sensitivity measures correlated across the two spatial frequencies, $r = 0.35$, $p < 0.001$. Consistent with measures made on the Sensory Station, Contrast Sensitivity was better at 6 cpd than 18 cpd, ($t(108) = 52.162$, $p < 0.001$), as measured by the Quick CSF method. At both spatial frequencies, Contrast Sensitivity correlated highly between the SS and QuickCSF assessment approaches (6 cpd, $r = 0.472$, $p < 0.001$; 18 cpd, $r = 0.509$, $p < 0.001$), and the absolute differences between the two assessments were rather small (6 cpd Δ .053; right Δ −0.007; binocular Δ 0.93), indicating external validity of this measure. Contrast Sensitivity thresholds for the second-stage factor analyses were taken as the average of the 6 and 18 cpd assessments.

3.1.3. Depth Perception (DP)

The Depth Perception task was a speeded-response task, and therefore, thresholds and average response times were computed for each of the three viewing conditions. As expected from previous research (Erickson et al., 2011), a one-way ANOVA revealed differences in the three viewing conditions ($F = 3.23$ $(2, 689)$, $p = 0.04$) such that, Depth Perception thresholds were better in the front-facing condition than in the left-facing condition ($p = 0.04$), and trending towards significance for the right-facing condition ($p = 0.08$). No difference was

Table 1
Correlations between Depth Perception thresholds and RTS in each of the three viewing conditions.

		Threshold			RT		
		Left	Right	Front	Left	Right	Front
Threshold	Left		0.44**	0.48**	−0.12	−0.11	−0.02
	Right			0.50**	−0.06	−0.04	0.02
	Front				−0.04	−0.02	−0.01
RT	Left					0.88**	0.76**
	Right						0.82**
	Front						

** p < 0.01, two-tailed.

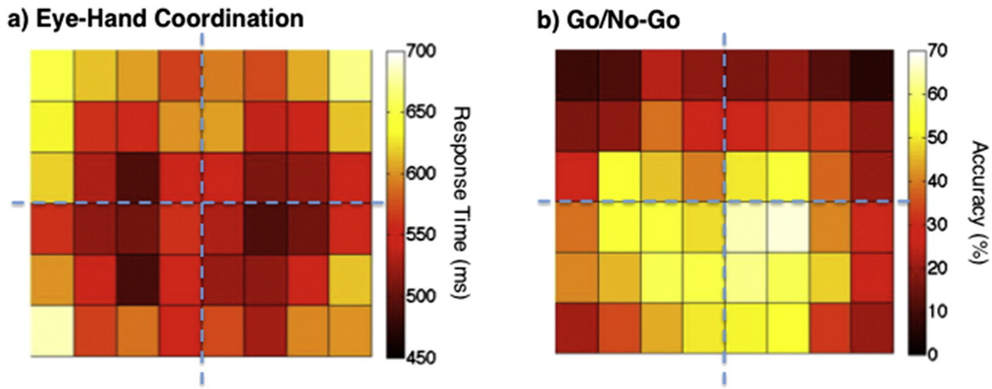

Fig. 2. Spatial performance profiles. a) Heatmap of mean response times in each of the 48 spatial positions in the Eye–Hand Coordination task. Average response times in the upper positions vs. lower positions (separated by the horizontal dotted line), and left positions vs. right positions (separated by the vertical dotted line) were compared. b) Heatmap of accuracy in each of the 48 positions in the Go/No-Go task. Average hit rates in the upper positions vs. lower positions (separated by the horizontal dotted line), and left positions vs. right positions (separated by the vertical dotted line) were compared.

present in the response times for the three conditions ($F = 0.54$ (2, 689), $p = 0.58$).

As a speeded response task, the comparison of disparity thresholds and response times offers a unique look at both shared and independent abilities within the same task. Interestingly, we found that while Depth Perception thresholds correlated strongly across the three viewing conditions, and response times correlated across the three viewing conditions, thresholds and response times did not correlate within or between conditions (Table 1). As thresholds and response times are largely independent, it may be expected that these reflect separable factors of perceptual and visual–motor abilities. To provide the most robust measures of Depth Perception thresholds and response times, the three-condition averages were used for our second-stage factor analysis.

3.1.4. Near–Far Quickness (NFQ)

Near–Far Quickness scores were computed as the total number of Landolt-C orientations that were correctly reported within 30 s. Across the 230 participants, the average score was 24 ($SD = 5$), with a range from 11 to 38. Response times for targets on the near screen were significantly faster than on the far screen (near: mean = 1077 ms; far: mean = 1434 ms; $t(229) = 12.785$, $p < 0.001$).

3.1.5. Dynamic Visual Acuity (DVA)

Dynamic Visual Acuity thresholds were computed as the minimum staircase duration at which a participant could accurately report the target direction of peripherally presented Landolt-Cs. Across our current sample the average score was 287 ms ($SD = 132$), with a range from 50 to 750 ms.

3.1.6. Perception Span (PS)

Perception Span scores indicate the number of correct minus incorrect spatial targets achieved by the participant over the 11 levels of the task. Across the sample, the average Perception Span score was 38 ($SD = 11$), with a range from 7 to 62. Almost all participants (≥94%) successfully passed levels 1–6. The passing percentage dropped to 81% on level 7, and then dropped precipitously to 43% on level 8. At this level, the number of flashing dots to be remembered was the same as in level 7, but the grid pattern of potential target locations became larger, increasing from 18 to 30.

3.1.7. Eye–Hand Coordination (EHC)

Eye–Hand Coordination scores were computed as the total time to touch each of the positions on the 6×8 array twice (96 total), with lower scores indicating better performance. Across our sample, the average score was 54,282 ms ($SD = 3792$), with a range from 45,315 ms to 65,252 ms. Group mean response times for each of the 48 positions are shown in Fig. 2a. With the grid positions being grouped into two halves (see the dotted line in Fig. 2a), participants' average response times were faster in the upper positions (554 ms) than the lower positions (577 ms; $t(229) = 8.605$, $p < 0.001$), and were also faster in the right positions (561 ms) than in the left positions (560 ms; $t(229) = 4.709$, $p < 0.001$).

3.1.8. Go/No-Go (GNG)

Go/No-Go was computed as the total number of hits (responses to green targets) minus the number of false alarms (responses to the red targets). Across our sample, the average Go/No-Go score was 23.4 ($SD = 11.0$), with a range from 2 to 55, indicating a very wide spectrum of abilities on this task. Hit rates were highest at the central positions, with accuracy falling off sharply towards the sides (Fig. 3b). With the grid positions being grouped into two halves (see the dotted line in Fig. 2b), hit rate was higher in the upper positions (43%) than in the lower positions (27%) ($t(229) = 13.388$, $p < 0.001$), but did not differ between the left (36%) and right positions (36%) ($t(229) = 0.141$, $p = 0.888$). The mean hit rate for each grid position in the Go/No-Go task correlated with the mean response time in the Eye–Hand Coordination task ($r = -0.78$, $p < 0.001$), such that faster RTs for a position in the Eye–Hand Coordination task corresponded with higher hit rates for that position in the Go/No-Go task.

In the entire sample of 7360 No-Go trials, there were only three false alarms. Therefore, the current task can only be considered in terms of overall achievement, and does not provide a measure of response inhibition failure, an important facet of response control (Boehler, Appelbaum, Krebs, Hopf, & Woldorff, 2010).

3.1.9. Hand Response Time (RT)

The *Hand Response Times* were computed as the mean of seven trials after outlier replacement. This yielded a group mean of 510 ms ($SD = 74$) across our current sample.

3.2. Cross-measures results

The results described above indicate that the Nike SPARQ Sensory Station battery produces a set of principled psychometric measures that can be used to better understand human perceptual and visual–motor abilities. Means and standard deviations for the 10 aggregate variables[1] from this battery are shown in Table 2, while the correlation structure among these variables is shown in Table 3. As can be seen in the correlation table, a number of the tasks share common variance,

[1] Note that the Depth Perception task recorded both a Response Time and a disparity threshold and therefore the nine tasks yielded ten measures.

Table 2
Mean and standard deviation of each measured variable in each condition. Variables with asterisks were the measures used for subsequent factor analysis. Note. N = 223 in the Hand Response Time task, while N = 230 in the rest of the tasks.

		M	SD
Static Visual Acuity (SVA)	Left monocular	−0.04	0.21
	Right monocular	−0.04	0.20
	Binocular	−0.14	0.15
	Average*	−0.07	0.14
Contrast Sensitivity (CS)	6 cpd	2.14	0.25
	18 cpd	1.45	0.28
	Average*	1.79	0.22
Depth Perception threshold (DP Thresh)	Facing left	83.3	75.4
	Facing right	79.6	76.1
	Facing front	66.7	69.9
	Average*	76.5	59.5
Depth Perception RT (DP RT)	Facing left	1429	680
	Facing right	1447	612
	Facing front	1489	610
	Average*	1455	594
Near–Far Quickness (NFQ)*		24	5
Dynamic Visual Acuity (DVA)*		287	132
Perceptual Span (PS)*		38	11
Eye–Hand Coordination (EHC)*		54,282	3792
Go/No-Go (GNG)*		23.4	11.0
Hand Response Time (HRT)*		510	74

and therefore, exploratory factor analysis was performed to better understand the latent constructs underlying this psychometric battery.

Principal-axis factor analysis revealed three interpretable factors based on the combination of scree test and eigenvalue scores (>1). These three factors explained 47.8% of the total variance for the 10 measures. Factor loadings above .299 are reported in Table 4, and estimated scores were computed for each participant on each of the three factors.

Based on the item loadings, a descriptive characterization of the three factors is as follows: the first factor (eigenvalue = 2.6, variance accounted = 19.4%) was labeled as "Visual–Motor Control," and consisted of strong loadings to Go/No-Go, Eye–Hand Coordination, Hand Response Time, and Perception Span. The second factor (eigenvalue = 1.9, variance accounted = 14.5%) was labeled as "Visual Sensitivity," and consisted of strong loadings to Contrast Sensitivity, Static Visual Acuity, and Depth Perception thresholds. The third factor (eigenvalue = 1.5, variance accounted = 13.7%) was labeled as "Eye Quickness," as it held strong loadings to Near–Far Quickness and Dynamic Visual Acuity.

3.3. Mapping variability in perceptual and visual–motor performance

To better understand variability in perceptual and visual–motor abilities across the current sample, we assessed factor-loading scores as a function of individual-difference characteristics. We examined eight individual-difference variables, which included gender, state anxiety, state negative affect, state positive affect, caffeine recency, food consumption recency, total sleep time, and time awake. Canonical correlations were first computed relating the optimal linear composite of the

Table 4
Varimax rotated factor matrix with individual task loading scores (thresholded at +/−.299).

	Factor		
	1	2	3
Eye–Hand Coordination	0.835		
Go/No-Go	−0.738		
Hand Response Time	0.562		
Perception Span	−0.484		
Average Static Visual Acuity		0.876	
Average Contrast Sensitivity		−0.628	
Average Depth Perception threshold		0.486	
Near–Far Quickness			0.939
Dynamic Visual Acuity			−0.636
Average Depth Perception Response Time			

Sensory Station performance variables (three factors) to the optimal linear composite of the eight individual-difference variables. Subsequent linear regression analyses were performed separately for each of the three factors. It should be noted that while the Sensory Stations record information about concussion history, the current sample of participants had very low incidences of past concussions. Since only about 5% of the participants had reported ever having a concussion, and all but two of these occurred more than a year prior to testing, concussions history was not included in the current analyses.

In the canonical correlation analysis (Tables 5 and 6), it was found that there was a significant relationship between the two domains (Wilks Lambda .7671, $F_{approx} = 2.25(24, 563.26)$, $p = 0.001$). This canonical correlation indicates that there is a single significant canonical dimension that relates perceptual and Visual–Motor Control to individual-difference characteristics.

Based on the significant canonical correlation findings, separate linear regression analyses were performed with each PFA factor as the dependent variable in order to relate individual-difference variables to the latent constructs measured by the Sensory Stations. Furthermore, based on previous findings demonstrating gender differences in psychomotor performance (Halpern, 2000; Thomas & French, 1985), regression analyses were designed with an initial base model that contained only gender, and a subsequent model that contained all other individual-difference variables.

As expected, the single parameter base model associating the first factor (Visual–Motor Control) with gender, produced a significant fit ($R^2 = 0.06$, $F(1,203) = 12.6$, $p < 0.001$). The addition of individual-difference variables in the second model produced a significant improvement in the fit above the base model (R^2 change: $F(7,196) = 3.0$, $p = 0.005$; combined model $R^2 = 0.15$). This improvement in the prediction of the model was driven principally by a significant positive relationship between Time Awake ($M = 271.02$ min, SD = 165.84 min) and scores for the first factor ($\beta = 0.286$, $p < 0.001$). This relationship indicated that Visual–Motor Control performance was better for participants that had been awake longer. No other individual-difference variables showed a significant relationship to the Visual–Motor Control factor.

Table 3
Correlations between the ten psychophysical variables recoded by the Sensory Station.

	CS	DP Thresh	DP RT	NFQ	DVA	PS	EHC	GNG	RT
SVA	−0.55**	0.26**	−0.05	−0.08	−0.18*	0.08	0.04	−0.01	0.06
CS		−0.19**	0.19**	0.08	0.17**	−0.05	−0.03	0.01	−0.12
DP Threshold			−0.06	−0.08	−0.02	−0.04	0.05	−0.06	0.09
DP RT				−0.23**	0.03	−0.06	0.10	−0.14*	0.04
NFQ					−0.34**	0.14*	−0.19**	0.24**	−0.15*
DVA						−0.08	0.04	−0.02	0.03
PS							−0.29**	0.35**	−0.11
EHC								−0.63**	0.36**
GNG									−0.28**

* $p < 0.05$, two-tailed.
** $p < 0.01$, two-tailed.

Table 5
Tests of canonical dimensions.

Dimension	Wilks L.	F	Hypoth. DF	Error DF	Sig. of F
1	0.76	2.25	24.00	563.26	0.001
2	0.92	1.08	14.00	390.00	0.368
3	0.98	0.81	6.00	190.00	0.560

Linear regression analyses on the second factor (Visual Sensitivity) did not produce a significant relationship for the base model including just gender ($p = 0.19$), or for the subsequent model containing the added individual-difference variables ($p = 0.55$). Linear regression analyses on the third factor (Eye Quickness) did not produce a significant relationship for the base model containing just gender ($p = 0.27$) or for the subsequent model including individual-difference variables ($p = 0.12$).

4. Discussion

In the current study, we sought to understand inter-individual variability in perceptual and visual–motor abilities by measuring behavioral performance on the Nike SPARQ Sensory Station battery and relating variability in this performance to individual-difference characteristics in a sample of 230 healthy college-aged participants. Nine perceptual and visual–motor abilities were assessed, and performance on each individual task was evaluated and, when possible, cross-validated with other independent assessments. Dimension reduction analysis revealed three interpretable factors: Visual–Motor Control, Visual Sensitivity and Eye Quickness. Among the three factors, inter-individual variability was primarily observed in Visual–Motor Control, such that males performed better than females. Additionally, participants who had been awake longer before completing the assessments performed better than those who woke closer in time to the testing session. In contrast, tasks underlying the Visual Sensitivity and Eye Quickness factors did not exhibit significant variability across the examined individual-difference variables. In the following sections we discuss the individual task results, then the latent constructs underlying the battery, and finally, how inter-individual variability relates to the current theories of perceptual and visual–motor function.

4.1. Perceptual and visual–motor abilities as measured by the Sensory Station

Nine individual tasks are built into the Sensory Station battery, including Static Visual Acuity, Contrast Sensitivity, Depth Perception, Near–Far Quickness, Dynamic Visual Acuity, Perceptual Span, Eye–Hand coordination, Go/No-Go, and Hand Response Time. These tasks assess abilities that have been indicated as important for sports performance (Erickson, 2012; Hitzeman & Beckerman, 1993). Among these measured abilities, Static Visual Acuity and Contrast Sensitivity tap into basic aspects of Visual Sensitivity and therefore are expected to remain relatively consistent across different modes of assessment. Therefore, to test the external validity of the Sensory Station measures, Static Visual Acuity and Contrast Sensitivity were cross-validated against other well-established external measures: the Snellen Eye Chart and QuickCSF task, respectively. In both cases the Sensory Station assessments showed modest, but significant correlations between the two different measurement techniques (*r*s between .4 and .5). Furthermore, the Sensory Station measures of basic visual functions yielded patterns of effects that are in line with previous reports using different measurement methods. Specifically, binocular Static Visual Acuity was better than monocular acuity of either eye (Cagenello, Arditi, & Halpern, 1993); Contrast Sensitivity at 6 cpd was better than 18 cpd, which is consistent with the conical Contrast Sensitivity function showing that medium-level spatial frequencies (~5–7 cpd) are optimally detected compared to low- or high-frequencies (Robson, 1966); Depth Perception thresholds were best in the front facing condition versus looking over the left or right shoulders (Erickson, Yoo, & Reichow, 2010; Yoo, Reichow, & Erickson, 2011); response times for targets on the near screen were significantly faster than on the far screen, supporting previous findings of asymmetries in perceptual processing for near and far targets (Vuilleumier, Valenza, Mayer, Reverdin, & Landis, 1998). These findings provide evidence for the external validity of the Sensory Station as a brief battery of basic visual sensory functions.

In addition to reproducing previously observed patterns of behavior effects, several of the Sensory Station measures also exhibited unique patterns. For example, both Depth Perception disparity thresholds and response times were correlated across the three viewing conditions; however, thresholds and response times did not cross-correlate with each other. This observation supports the notion that response speed and perceptual sensitivity are separable facets of performance (Handy, Kingstone, & Mangun, 1996; O'Connor & Burns, 2003), even when measured within the same task. In addition, the score of Near–Far Quickness correlated with the Depth Perception Reaction Times, but not the Depth Perception thresholds. This further confirmed that response speed and perceptual sensitivity are separable factors influencing human performance.

It should also be noted that some of the visual–sensory tasks exhibited limitations due to the staircase procedure employed in the Sensory Station. For instance, a large number of participants were at ceiling at the 6 cpd Contrast Sensitivity task, and therefore the dynamic range of contrast stimuli tested may still require further refinement. Another possible limitation is that the Dynamic Visual Acuity task produced the most variable individual participant staircase functions, but only entailed a single estimate. As such, there may be a need to further cross-validate and possibly refine this assessment.

In addition to measures of Visual Sensitivity, the Sensory Station also assessed visual–motor abilities through the Eye–Hand Coordination, Go/No-Go, Perception Span and Hand Response Time tasks. The Eye–Hand coordination task required participants to respond as fast as possible to a target presented at one of the 6×8 grid positions. RTs were faster for the area in the center of the array around participants' “hands ready” positions, consistent with previous findings that spatial–temporal coupling of eye and hand movements is optimal for picking up visual information near the position of the hand and positions late in the hand's trajectory (Binsted, Chua, Helsen, & Elliott, 2001). The Go/No-Go task involved the same 6×8 grid and accordingly those positions with faster RTs in the Eye–Hand Coordination task were also associated with higher hit rates in the Go/No-Go task. Average reaction times on the Eye–Hand Coordination task and hit rates on the Go/No-Go task also correlated with performance on the Hand Response Time task. The Hand Response Time task involved moving one's hand/arm across the body midline and hitting the target position as fast as possible. An earlier study (Fisk & Goodale, 1985) found that reaching targets across the body midline were slower than reaching targets on

Table 6
Standardized canonical coefficients.

	Dimension 1
Performance variables	
Factor 1	0.91
Factor 2	0.30
Factor 3	−0.24
Individual difference variables	
Gender	0.64
Caffeine recency	−0.10
Food consumption recency	−0.30
Total sleep time	0.04
Time awake	−0.68
STAI state anxiety	0.23
PANAS state negative affect	0.16
PANAS state positive affect	−0.23

the same side of the reaching arm. While these two conditions required the same amount of eye movements, the eye movements associated with contralateral arm movements were still slower than those associated with ipsilateral arm movements, indicating that a shared control mechanism links eye movements and limb movements (Fisk & Goodale, 1985; for a review, see Carey, 2000). Therefore, the strong correlations between the three Sensory Station tasks suggests that these measures might tap into a common ability that involves control of eye and hand/arm coordination for responding to spatially distributed stimuli.

Like the visual–sensory tasks, some of the visual–motor tasks also show potential limitations due to the settings in the Sensory Station. In particular, caution is needed when interpreting the results from the Go/No-Go task. In this task, a 'Go' response must be made within 500 ms. This built-in time limit is substantially shorter than the average RT (565 ms) in the Eye–Hand Coordination task, and is close to the shorter extreme in the RT distribution (472–680 ms) from the Eye–Hand Coordination task. The short time limit made it difficult for participants to make successful 'Go' responses (average hit rate was only 36% across all positions); therefore, there was relatively little need to invoke response inhibition, and virtually no false alarms were recorded (three false alarms out of 7360 total responses). Due to the lack of false alarms, this task may not be a valid measure of response inhibition, but instead, may be best considered as a reflection of successful action under the presence of inhibition.

4.2. Factor structure of perceptual and visual–motor abilities as measured by the Sensory Station

Dimension reduction approaches are widely utilized to distil a battery of psychological measures into a set of common latent factors that overlap in an unknown way over a particular set of tasks. Historically, batteries that incorporate perceptual and visual–motor skills are described as consisting of a limited number of independent 'psychomotor' factors (e.g., Boyle & Ackerman, 2004; Fleishman & Hempel, 1956; Guilford, 1958) that, in turn, overlap with a more general cognitive factor (Carretta & Ree, 1997; Chaiken, Kyllonen, & Tirre, 2000; Ree & Carretta, 1994). Despite this insight, relatively few of the existing multi-test performance batteries have specifically included measures of low-level sensory functions, such as visual acuity, Contrast Sensitivity, and depth perception, despite the critical role that basic visual sensory abilities play in most human performance contexts, and evidence that they modulate a number of other higher-level perceptual and cognitive abilities (Daffner et al., 2013; Skeel, Schutte, van Voorst, & Nagra, 2006). As such, the Sensory Station battery offers a unique view into human abilities.

In the current study, factor analysis was performed to identify the latent constructs underlying the Sensory Station psychometric battery. This analysis produced three factors that accounted for nearly half of the overall variance for the ten measures. The first factor consisted of heavy loadings to the Go/No-Go, Eye–Hand Coordination, Perception Span, and Hand Reaction Time tasks. Because these tasks all rely on rapid and accurate processing of distributed visual information and subsequent motor responses, this factor was interpreted as reflecting 'Visual–Motor Control' abilities. Previous research on human psychomotor abilities has frequently identified Visual–Motor Control to be among the latent factors underlying human performance (e.g., Chaiken et al., 2000) that are also among the most significant predictors of real-world outcomes (Griffin & Koonce, 1996; Hunter & Hunter, 1984).

The second factor identified in our analyses held strong weightings to the Contrast Sensitivity, Static Visual Clarity, and Depth Perception threshold tasks. These tasks all measured the minimum resolvable visual stimuli, and therefore, this factor was interpreted as reflecting 'Visual Sensitivity'. Such low-level visual sensory abilities are often considered the foundation upon which higher-level functions are built (Valentijn et al., 2005). For example, age-related deficits in cognitive abilities, as measured by fluid intelligence, have been shown to be at least partly associated with declines in the basic visual sensory functions, such as visual acuity and Contrast Sensitivity (Clay et al., 2009).

The third factor consisted of strong weightings to the Near–Far Quickness and Dynamic Visual Acuity tasks. Near–Far Quickness is an assessment of the speed at which eyes are able to change focus between near and far distances, while Dynamic Visual Acuity requires the eyes to quickly move away from a central fixation and foveate to a brief peripheral stimulus. As such, these tasks measure quick ocular–motor accommodation and rapid reallocation of visual attention to brief stimuli, and therefore, this factor was interpreted as reflecting 'Eye Quickness'. This factor may be related to the notion of 'perceptual speed' discussed in the psychometric literature (Ackerman, 1988; Salthouse, 2000, 2013). Psychometric researchers have dissociated 'perceptual speed' from the general 'processing speed', wherein the former is often assessed by simple tasks in which everyone would be perfect if there were no time limits, with the test score consisting of the number of items correctly completed in the specified time. In contrast, 'processing speed' often refers to cognitive processing constraints when performing moderately complex tasks, and thus is contingent on the relevant cognitive skills required in the specific task (Ackerman, 1988; Salthouse, 2000, 2013). In the current study, the tasks involved in the Eye Quickness factor largely depend on oculo-motor coordination, and are therefore less susceptible to variability in cognitive abilities.

The observation that three factors accounted for roughly half of the overall variance indicates a modest utility in this descriptive dimension reduction approach, and is generally consistent with the notion that a small number of latent constructs underlie a larger set of psychomotor abilities (e.g., Chaiken et al., 2000). An important consideration, however, stems from the specific methodology employed in the Sensory Station. Namely, all of the tasks associated with the first factor require responses on the large 42-inch touch sensitive screen, while all the tasks associated with the second factor utilize staircase procedures. Because of this, care should be taken in interpreting the reported constructs of perceptual and visual–motor abilities as measured by the Sensory Station. Nevertheless, the three factors are largely consistent with both our a priori expectations and the larger literature on psychomotor abilities, and also include basic visual sensory abilities that have been largely overlooked in past psychomotor studies. These factors thus provide an initial set of perceptual and visual–motor ability metrics that can be used to further explore the variability of human performance.

4.3. Individual differences

There are a large number of fixed (e.g., gender) and variable (e.g., emotional state) individual-difference characteristics that may lead to better or worse perceptual or visual–motor performance. To understand how these characteristics impact perceptual and visual–motor performance, the three latent factors described above were related to a small set of individual-difference variables, including gender, emotional state, sleep and circadian factors, and recent consumption history for each participant prior to the start of their psychomotor assessment. From this analysis we observed that inter-individual variability was only seen for tasks that involved some aspect of Visual–Motor Control. In particular, we found that the strongest predictor of performance on Visual–Motor Control tasks was gender. While the absolute magnitude of this gender difference was rather modest (only 6% of the performance variance for this factor), this finding that males performed better than females is consistent with past findings demonstrating that males typically perform better on tasks that involve fast ballistic movements of the arms, including throwing and catching (Thomas & French, 1985), as well as simple motor responses (Dykiert, Der, Starr, & Deary, 2012). It is also of specific interest here that minimal gender differences were seen in any of the other tasks, indicating that these abilities are comparable between the sexes.

Beyond gender, differences in the amount of time each participant had been awake also had a significant predictive relationship with Visual–Motor Control. The finding that Visual–Motor Control performance was better for individuals tested at longer wake times is consistent with proposed impact of circadian variations on physiological and cognitive processes, which report performance to be worse in the morning and peak later in the day (Valdez et al., 2005). These circadian influences depend on task complexity, variability, and duration (Blatter & Cajochen, 2007), which may account for the lack of relationship with the Visual Sensitivity or Eye Quickness factors. Nonetheless, since intra-individual differences were not tested (i.e. repeated testing at different wake intervals for the same individual, e.g., Valdez et al., 2012), and since participants performed only during daytime hours in the context of their typical, unaltered sleep patterns, further research is warranted to more fully map out the relationship between sleep and performance on the metrics from this perceptual and visual–motor battery.

4.4. Implications

While a large number of research protocols have been used to evaluate and explore the factors that influence human perceptual and visual–motor performance, it is difficult to generalize findings across different studies because of the diversity in methodology and tasks that are used. The Nike Sensory Station provides a unified platform that bridges these limitations and allows perceptual and visual–motor abilities to be tested in a quick and engaging way. Because this tool is deployed in a number of different assessment and training programs, and provides normative data across different subject populations, the current findings offer important applied implications for researchers and practitioners.

For example, understanding the structure of perceptual and visual–motor abilities may help to identify the factors that discriminate experts from novices, thereby providing guidance in personnel selection. Among the three latent factors underlying perceptual and visual–motor abilities found here, Visual Sensitivity (consisting of Static Visual Acuity, Contrast Sensitivity, and Depth Perception) is largely limited by the physical characteristics of the visual system. These aspects of visual function have traditionally been referred to as visual “hardware” (Abernethy, 1986) because they are thought to reflect the physical characteristics of the visual system. Although adequate visual “hardware” is necessary for completing dynamic tasks, above normal visual “hardware” does not necessarily lead to better performance (Abernethy & Wood, 2001; Wood & Abernethy, 1997). In contrast, elite performers and novices are most often distinguished by their visual “software”, which reflects the strategies that performers have developed to cope with the unique processing demands of their sport (Abernethy, 1986). These “software” skills more closely mirror the Visual–Motor Control abilities (Eye–Hand Coordination, Go/No-Go, Perception Span, and Hand Reaction Time) in the current study. Moreover, there is evidence showing that these Visual–Motor Control abilities can be substantially improved through training (Abernethy, 1986; Abernethy & Wood, 2001; Erickson et al., 2011; Krasich et al., under review; Wood & Abernethy, 1997), while substantially less evidence has demonstrated the capacity for improvement in abilities relating to Visual Sensitivity (though see Deveau, Lovcik, & Seitz, 2014; Deveau & Seitz, 2014).

The current findings illustrate the structure of perceptual and visual–motor abilities while also revealing that the Visual–Motor Control abilities are more influenced by individual differences, including gender and testing time. Thus, training programs targeting Visual–Motor Control abilities may show greater effectiveness if they take into consideration these individual differences. In addition, the current study provides a robust sample of healthy, non-athlete individuals and thus may provide comparative information for other subject populations. In addition, as observed in the hockey study by Poltavski and Biberdorff (2014) and the concussion study by Harpham and colleagues (2014) discussed above, performance on the Sensory Station battery has specific predictive relationships with important real-world outcomes. By incorporating the gender and time-of-day covariates observed in the current study, future research may gain a greater level of sensitivity for establishing other meaningful predictive relationships.

4.5. Conclusions

In the present study, we performed an exploratory analysis of inter-individual variability in human perceptual and visual–motor abilities. By leveraging the rapid assessment available through the Sensory Station, we were able to test a large sample of 230 participants, and perform principled analyses of variability across this population. By performing dimension reduction and comparing performance across individuals, we have described visual and motor functions in a normative sample and found that inter-individual variability is primarily expressed though differences in Visual–Motor Control abilities. These findings illustrate sources of variability and stability in perceptual and visual–motor functions and provide a set of performance metrics that can be used to further explore cross-sectional and longitudinal variability in applied settings.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.actpsy.2015.02.005.

Acknowledgments

This research was funded by grant support to L.G.A. and S.R.M through DARPA grant D12AP00025-002. Thanks to Annie Apple, Ben Ramger, Floyd Wilks Jr., Laura Holton, Clara Colombatto and Eliza Gentzler for the assistance with data collection, and to all of the experimental participants. Thanks also to Adam Biggs, Elise Darling, and Stephen Adamo for their help in setting up these experiments.

References

Abernethy, B. (1986). Enhancing sports performance through clinical and experimental optometry. *Clinical & Experimental Optometry*, *69*(5), 189–196.

Abernethy, B., & Wood, J. M. (2001). Do generalized visual training programmes for sport really work? An experimental investigation. *Journal of Sports Sciences*, *19*(3), 203–222.

Ackerman, P. L. (1988). Determinants of individual differences during skill acquisition: Cognitive abilities and information processing. *Journal of Experimental Psychology. General*, *117*(3), 288.

Barnes, L. L., Harp, D., & Jung, W. S. (2002). Reliability generalization of scores on the Spielberger state-trait anxiety inventory. *Educational and Psychological Measurement*, *62*(4), 603–618.

Binsted, G., Chua, R., Helsen, W., & Elliott, D. (2001). Eye–hand coordination in goal-directed aiming. *Human Movement Science*, *20*(4), 563–585.

Blatter, K., & Cajochen, C. (2007). Circadian rhythms in cognitive performance: Methodological constraints, protocols, theoretical underpinnings. *Physiology & Behavior*, *90*(2), 196–208.

Boehler, C. N., Appelbaum, L. G., Krebs, R. M., Hopf, J. -M., & Woldorff, M. G. (2010). Pinning down response inhibition in the brain—Conjunction analyses of the Stop-signal task. *NeuroImage*, *52*(4), 1621–1632.

Bolmont, B., Gangloff, P., Vouriot, A., & Perrin, P. P. (2002). Mood states and anxiety influence abilities to maintain balance control in healthy human subjects. *Neuroscience Letters*, *329*(1), 96–100.

Boyle, M. O., & Ackerman, P. L. (2004). *Individual differences in skill acquisition.* Skill acquisition in sport: Research, theory and practice, 84–92.

Breimhorst, M., Falkenstein, M., Marks, A., & Griefahn, B. (2008). The relationship between poor sleep and inhibitory functions indicated by event-related potentials. *Experimental Brain Research*, *187*(4), 631–639.

Cagenello, R., Arditi, A., & Halpern, D. L. (1993). Binocular enhancement of visual acuity. *Journal of the Optical Society of America. A*, *10*(8), 1841–1848.

Carey, D. P. (2000). Eye–hand coordination: Eye to hand or hand to eye? *Current. Biology*, *10*(11), R416–R419.

Carretta, T. R., & Ree, M. J. (1997). Expanding the nexus of cognitive and psychomotor abilities. *International Journal of Selection and Assessment*, *5*(3), 149–158.

Carrier, J., & Monk, T. H. (2000). Circadian rhythms of performance: New trends. *Chronobiology International*, *17*(6), 719–732.

Chaiken, S. R., Kyllonen, P. C., & Tirre, W. C. (2000). Organization and components of psychomotor ability. *Cognitive Psychology*, *40*(3), 198–226. http://dx.doi.org/10.1006/cogp.1999.0729.

Clay, O. J., Edwards, J. D., Ross, L. A., Okonkwo, O., Wadley, V. G., Roth, D. L., et al. (2009). Visual function and cognitive speed of processing mediate age-related decline in memory span and fluid intelligence. *Journal of Aging and Health*, *21*(4), 547–566.

Daffner, K. R., Haring, A. E., Alperin, B. R., Zhuravleva, T. Y., Mott, K. K., & Holcomb, P. J. (2013). The impact of visual acuity on age-related differences in neural markers of early visual processing. *NeuroImage*, *67*, 127–136.

Datta, V., Chang, A., Mackay, S., & Darzi, A. (2002). The relationship between motion analysis and surgical technical assessments. *The American journal of surgery*, *184*(1), 70–73.

Deveau, J., Lovcik, G., & Seitz, A. R. (2014). Broad-based visual benefits from training with an integrated perceptual-learning video game. *Vision Research*, *99*, 134–140.

Deveau, J., & Seitz, A. R. (2014). Applying perceptual learning to achieve practical changes in vision. *Frontiers in Psychology*, *5*.

Dorr, M., Lesmes, L. A., Lu, Z. L., & Bex, P. J. (2013). Rapid and reliable assessment of the contrast sensitivity function on an iPad. *Investigative ophthalmology & visual science*, *54*(12), 7266–7273.

Dykiert, D., Der, G., Starr, J. M., & Deary, I. J. (2012). Sex differences in reaction time mean and intraindividual variability across the life span. *Developmental Psychology*, *48*(5), 1262.

Erickson, G. B. (2012). Give athletes a shot at better vision: Whether they shoot foul shots or target rifles, your athletic patients require the best vision to stay at the top of their game. *Review of Optometry*, *149*(5), 83–89.

Erickson, G. B., Citek, K., Cove, M., Wilczek, J., Linster, C., Bjarnason, B., et al. (2011). Reliability of a computer-based system for measuring visual performance skills. *Optometry*, *82*(9), 528–542. http://dx.doi.org/10.1016/j.optm.2011.01.012.

Erickson, G., Yoo, H., & Reichow, A. (2010). A comparison of stereoacuity at 6 m of collegiate baseball players in primary gaze and batting stance. *Journal of Vision*, *10*(7), 374-374.

Fabrigar, L. R., Wegener, D. T., MacCallum, R. C., & Strahan, E. J. (1999). Evaluating the use of exploratory factor analysis in psychological research. *Psychological methods*, *4*(3), 272.

Fisk, J. D., & Goodale, M. A. (1985). The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. *Experimental Brain Research*, *60*(1), 159–178.

Fleishman, E. A., & Hempel, W. E. (1956). Factorial analysis of complex psychomotor performance and related skills. *Journal of Applied Psychology*, *40*(2), 96.

Fredrickson, B. L., & Branigan, C. (2005). Positive emotions broaden the scope of attention and thought action repertoires. *Cognition & Emotion*, *19*(3), 313–332.

Gilrein, T. (2014). *Reliable change indices of visual and sensory performance measures.* Chapel Hill: (M.A.), University of North Carolina.

Griffin, G. R., & Koonce, J. M. (1996). Review of psychomotor skills in pilot selection research of the US military services. *The International Journal of Aviation Psychology*, *6*(2), 125–147.

Guilford, J. (1958). A system of the psychomotor abilities. *The American Journal of Psychology*, *71*(1), 164–174.

Halpern, D. F. (2000). *Sex differences in cognitive abilities.* Psychology press.

Halpern, D. F., Straight, C. A., & Stephenson, C. L. (2011). Beliefs about cognitive gender differences: Accurate for direction, underestimated for size. *Sex Roles*, *64*(5–6), 336–347.

Han, D. H., Park, H. W., Kee, B. S., Na, C., Na, D. H. E., & Zaichkowsky, L. (2011). Performance enhancement with low stress and anxiety modulated by cognitive flexibility. *Psychiatry investigation*, *8*(3), 221–226.

Handy, T. C., Kingstone, A., & Mangun, G. R. (1996). Spatial distribution of visual attention: Perceptual sensitivity and response latency. *Perception & Psychophysics*, *58*(4), 613–627.

Harpham, J. A., Mihalik, J. P., Littleton, A. C., Frank, B. S., & Guskiewicz, K. M. (2014). The effect of visual and sensory performance on head impact biomechanics in college football players. *Annals of Biomedical Engineering*, *42*(1), 1–10.

Hashemi, H., Khabazkhoob, M., Jafarzadehpur, E., Emamian, M. H., Shariati, M., & Fotouhi, A. (2012). Contrast sensitivity evaluation in a population-based study in Shahroud, Iran. *Ophthalmology*, *119*(3), 541–546.

Hitzeman, S. A., & Beckerman, S. A. (1993). What the literature says about sports vision. *Optometry Clinics: The Official Publication of the Prentice Society*, *3*(1), 145.

Hunter, J. E. (1986). Cognitive ability, cognitive aptitudes, job knowledge, and job performance. *Journal of Vocational Behavior*, *29*(3), 340–362.

Hunter, J. E., & Hunter, R. F. (1984). Validity and utility of alternative predictors of job performance. *Psychological Bulletin*, *96*(1), 72.

Jarraya, M., Jarraya, S., Chtourou, H., Souissi, N., & Chamari, K. (2013). The effect of partial sleep deprivation on the reaction time and the attentional capacities of the handball goalkeeper. *Biological Rhythm Research*, *44*(3), 503–510.

Johnston, P. J., & Catano, V. M. (2002). Psychomotor abilities tests as predictors of training performance. *Canadian Journal of Behavioural Science/Revue Canadienne Des Sciences du Comportement*, *34*(2), 75.

Kaplan, S., Bradley, J. C., Luchman, J. N., & Haynes, D. (2009). On the role of positive and negative affectivity in job performance: A meta-analytic investigation. *Journal of Applied Psychology*, *94*(1), 162–176 (463).

Kauranen, K., & Vanharanta, H. (1996). Influences of aging, gender, and handedness on motor performance of upper and lower extremities. *Perceptual and Motor Skills*, *82*(2), 515–525.

Kimura, D. (1999). *Sex and cognition.* Cambridge MA: MIT Press/Bradford Books.

King, R. E., Carretta, T. R., Retzlaff, P., Barto, E., Ree, M. J., & Teachout, M. S. (2013). Standard cognitive psychological tests predict military pilot training outcomes. *Aviation Psychology and Applied Human Factors*, *3*(1), 28.

Krasich, K., Ramger, B., Holton, L., Wang, L., Mitroff, S. R., & Appelbaum, L. G. (2015w). *Perceptual and visual–motor learning in a computerized training battery.* (under review).

Lesmes, L. A., Lu, Z. -L., Baek, J., & Albright, T. D. (2010). Bayesian adaptive estimation of the contrast sensitivity function: The quick CSF method. *Journal of Vision*, *10*(3).

Leue, A., & Beauducel, A. (2011). The PANAS structure revisited: on the validity of a bifactor model in community and forensic samples. *Psychological assessment*, *23*(1), 215.

Maan, Z., Maan, I., Darzi, A., & Aggarwal, R. (2012). Systematic review of predictors of surgical performance. *British Journal of Surgery*, *99*(12), 1610–1621.

Mann, D. T., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual–cognitive expertise in sport: A meta-analysis. *Journal of Sport and Exercise Psychology*, *29*(4), 457.

Matchock, R. (2010). Circadian and sleep episode duration influences on cognitive performance following the process of awakening. *International Review of Neurobiology*, *93*, 129–151.

Matchock, R. L., & Mordkoff, J. T. (2007). Visual attention, reaction time, and self-reported alertness upon awakening from sleep bouts of varying lengths. *Experimental Brain Research*, *178*(2), 228–239.

Muraven, M., & Baumeister, R. F. (2000). Self-regulation and depletion of limited resources: Does self-control resemble a muscle? *Psychological Bulletin*, *126*(2), 247.

O'Connor, T. A., & Burns, N. R. (2003). Inspection time and general speed of processing. *Personality and Individual Differences*, *35*(3), 713–724.

Poltavski, D., & Biberdorff, D. (2014). The role of visual perception measures used in sports vision programs in predicting actual game performance in Division I collegiate hockey players. *Journal of Sports Sciences*. http://dx.doi.org/10.1080/02640414.2014.951952 (epub ahead of print).

Raglin, J. S. (1992). 9: Anxiety and sport performance. *Exercise and Sport Sciences Reviews*, *20*(1), 243–274.

Ree, M. J., & Carretta, T. R. (1994). The correlation of general cognitive ability and psychomotor tracking tests. *International Journal of Selection and Assessment*, *2*(4), 209–216.

Robson, J. (1966). Spatial and temporal contrast-sensitivity functions of the visual system. *Journal of the Optical Society of America*, *56*(8), 1141–1142.

Ruff, R. M., & Parker, S. B. (1993). Gender-and age-specific changes in motor speed and eye–hand coordination in adults: normative values for the Finger Tapping and Grooved Pegboard Tests. *Perceptual and Motor Skills*, *76*(3c), 1219–1230.

Salthouse, T. A. (2000). Aging and measures of processing speed. *Biological Psychology*, *54*(1), 35–54.

Salthouse, T. A. (2013). *Evaluating the correspondence of different cognitive batteries.* Assessment.

Skeel, R. L., Schutte, C., van Voorst, W., & Nagra, A. (2006). The relationship between visual contrast sensitivity and neuropsychological performance in a healthy elderly sample. *Journal of Clinical and Experimental Neuropsychology*, *28*(5), 696–705.

Skinner, N., & Brewer, N. (2002). The dynamics of threat and challenge appraisals prior to stressful achievement events. *Journal of Personality and Social Psychology*, *83*(3), 678.

Skinner, N., & Brewer, N. (2004). Adaptive approaches to competition: Challenge appraisals and positive emotion. *Journal of Sport and Exercise Psychology*, *26*(2), 283–305.

Spielberger, C. D., Gorsuch, R. L., & Lushene, R. E. (1970). *State-trait anxiety inventory.* Palo Alto. Cal.: Consulting Psychologists Press.

Spielberger, C. D. (2010). *State- Trait Anxiety Inventory.* Inc: John Wiley & Sons.

Thomas, J. R., & French, K. E. (1985). Gender differences across age in motor performance: A meta-analysis. *Psychological Bulletin*, *98*(2), 260.

Valdez, P., Ramírez, C., García, A., Talamantes, J., Armijo, P., & Borrani, J. (2005). Circadian rhythms in components of attention. *Biological rhythm research*, *36*(1–2), 57–65.

Valdez, P., Ramírez, C., & García, A. (2012). Circadian rhythms in cognitive performance: Implications for neuropsychological assessment. *ChronoPhysiology and Therapy*, *2*, 81–92.

Valentijn, S. A., Van Boxtel, M. P., Van Hooren, S. A., Bosma, H., Beckers, H. J., Ponds, R. W., et al. (2005). Change in sensory functioning predicts change in cognitive functioning: Results from a 6-year follow-up in the Maastricht Aging Study. *Journal of the American Geriatrics Society*, *53*(3), 374–380.

Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S., & Roberts, B. (2010). Are expert athletes 'expert' in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Applied Cognitive Psychology*, *24*(6), 812–826.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, *117*(2), 250.

Vuilleumier, P., Valenza, N., Mayer, E., Reverdin, A., & Landis, T. (1998). Near and far visual space in unilateral neglect. *Annals of Neurology*, *43*(3), 406–410.

Watson, D., & Clark, L. A. (1999). *The PANAS-X: Manual for the positive and negative affect schedule-expanded form.*

Wood, J. M., & Abernethy, B. (1997). An assessment of the efficacy of sports vision training programs. *Optometry and Vision Science*, *74*(8), 646–659.

Wood, J. M., Tataryn, D. J., & Gorsuch, R. L. (1996). Effects of under- and overextraction on principal axis factor analysis with varimax rotation. *Psychological Methods*, *1*(4), 354.

Wright, T. A., Cropanzano, R., & Meyer, D. G. (2004). State and trait correlates of job performance: A tale of two perspectives. *Journal of Business and Psychology*, *18*(3), 365–383.

Yoo, H., Reichow, A., & Erickson, G. (2011). Stereoacuity of athletes in primary and non-primary gazes. *Journal of Vision*, *11*(11), 331-331.