Validation Affordances: Keeping the Eye on 3D Virtual-Simulation Baseballs

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ABSTRACT

A persistent challenge to technology-enhanced learning is a general need for evidence-based ecological validation protocols—especially as it pertains to transfer-of-training for serious video games and virtual simulators. It is often missed that the critical objective in achieving ecological validity in virtual simulation trainers is not necessarily to maximize realism but to optimize training by targeted and deliberate stimuli, and that validation must be against operational simuland referents as well as affordance referents. That is, validation must ensure not only that the body of knowledge of real operational environments being simulated (i.e., simuland referents) is properly selected, specified, and codified in computable models but also that quality measures of human sensory detection instigated by virtual environments are consistent with those afforded by corresponding real/live simulands (i.e., affordance referents). In this first-of-its-kind exploratory pilot study, a part-task hybrid *simulation-couple* paradigm (i.e., virtual simulator in tandem with mechanical simulator counterpart) was implemented to garner and establish oculomotor affordance referents relative to ecologically-valid 60-mph live fastballs in the baseball batting task as well as to instigate and measure horizontal eye movements relative to corresponding virtual fastballs. Results indicate virtual fastballs in full-size 3D stereo theater afford similar overt attentional responses as live fastballs at modest speeds but not at faster speeds. Onset times of catchup saccades, succeeding smooth pursuit, while observing off-center incoming virtual fastballs, lagged those while observing live fastballs—suggesting possible accommodative-vergence impairment induced by the fixed focal plane of 3D stereo display. Results offer nominal evidence of limited ecological validity for 3D stereo virtual environments involving horizontal eye-movement tasks while observing objects moving in depth—demonstrating the relevance of affordance referents in selective ecological validation of virtual stimuli.

ABOUT THE AUTHORS

Dr. Ricardo A. "Ric" Roca is a systems-engineering consultant specialized in modeling & simulation (M&S) research & development. Dr. Roca has over 32 years of professional experience, primarily in federally-funded DoD M&S projects. He earned a B.S.E. in Electrical Engineering from Tulane University, an M.S. in Systems Engineering from George Mason University, and a Ph.D. in Modeling & Simulation Engineering from Old Dominion University. His research interests include objective conceptual modeling with dimensional analysis for specification, validation, refurbishment, and repurposing of computable models as well as generation and validation of affordance referents with analog-virtual simulation-couples for virtual simulation trainers, serious games, and technology enhanced learning in academia, sports, military, and industry.

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INTRODUCTION

Virtual simulation training formats, including serious video games, generally suffer from a lack of ecological validity (i.e., relevant realism or context) (Williams, Davids, Burwitz, & Williams, 1993) and of formal transfer-of-training (ToT) validation protocols (Peck, 2011)—both of which rely on context referents and domain expertise that can be difficult to capture, specify, and codify into software computable models. Additionally, increasing model fidelity arbitrarily in a simulated environment does not necessarily translate into more effective virtual simulation trainers (Allen, Buffardi, & Hays, 1991; Gross, 1999; Rehman, 1995). That is, the critical objective for part-task simulation fidelity specification is not to necessarily maximize realism but to optimize training (Bunker, 1978; Orlady, Hennessy, Obermayer, Vreuls, & Murphy, 1988; Rehman, 1995). These findings have prompted technology-enhanced learning practitioners to explore alternatives to instigate and measure human visual-orienting (and other sensory) responses that can be related to attention, perception, and learning underlying ecological validity and transfer-of-training (ToT) validation protocols.

A case in point is training for the baseball batting task which is generally agreed to be one of the most difficult visuo-motor tasks in sport (Burroughs, 1984). Ted Williams—one of the greatest and most celebrated hitters in baseball history—declared, “I think without question the hardest single thing to do in sport is to hit a baseball” (Peterson, 2011). Accordingly, “keeping your eye on the ball” has been a long-standing tenet in baseball batting (Smith, 1954). But an equally long-standing and persistent question that has remained unresolved is “how to train the eyes to do this?” That is, how should this be done without formal protocols for objectively conditioning, measuring, and/or evaluating eye-on-ball coordination (Bolin, 1948).

Alternative simulation approaches to traditional eye-on-ball exercises (e.g., soft toss, number-marked tennis balls, etc.) have been considered—including still photographs, videos, video games, and virtual-reality formats among others (Gray, 2002; Hyllegard, 1991; Shank & Haywood, 1987). Video game formats typically present animations of the pitcher wind-up followed by the pitched baseball that increases in size to simulate its approach. However, these and other 2D formats cause batters to maintain their gaze on the screen since the ball never leaves the screen. This not only prevents them from developing the skill to follow the ball into contact with the bat but also risks the development of bad habits (i.e., negative ToT) as it would reinforce looking straight ahead in the pitcher’s direction throughout the entire ball trajectory. Not surprisingly, these formats have led to inconsistent results—prompting for more research that examines the effects of fidelity and dimensionality on ecological validity within applied sport contexts (Williams et al., 1993).

Ecological validity for ball-tracking sports implicates oculomotor affordances given the relationship of visual orienting to attentional and cognitive processes (Lang, Simnons, & Balaban, 1997). In this first-of-its-kind exploratory pilot study it was postulated that computable models underlying simulated fastballs should be codified and validated according to the body of knowledge on fastballs (i.e., simuland referents), to include kinematics, air resistance, etc., but that they must also be validated according to the body of knowledge on oculomotor affordances consisting of batters’ eye movement interactions with live/real fastballs (i.e., affordance referents). To establish oculomotor affordance referents of live fastballs and validate the virtual-fastball affordances (and facilitate the collection of pilot data from where statistical power for future studies could be calculated), a hybrid *simulation-couple* was implemented, consisting of a 3D stereo virtual simulator in tandem with an analog simulator (i.e., pitching machine) both configured and calibrated to provide 60-mph fastball stimuli. Hybrid simulation has been implemented to measure ecological validity in other contexts (van der Ham, Faber, Venselaar, van Kreveld, & Loffler, 2015).

Affordances and M&S Validation

An “affordance” refers to what an environment offers an individual to enable his/her capabilities (e.g., a ladder affords climbing to a healthy adult but not to a crawling infant) (Gibson, 1979; McGrenere & Ho, 2000) and, when extended to human-machine interaction, a “perceived affordance” refers to inherent action possibilities and to likely interactions with particular objects (e.g., throw ball and sit on chair but not vice-versa) (McGrenere & Ho, 2000; Norman, 1999). In particular, visual search/orienting is an overt visual attention affordance (Geisler & Cormack, 2011) which is the first step in processing stimulus information (Lang et al., 1997). Orienting seems to be related to attentional processes and can be used to study attention itself, attentional dysfunction (Graham & Hackley, 1991; Lang et al., 1997), and visual attention/orientation training. This is relevant to practical visualization design problems and useful to the distinction between validation of operational systems (e.g., tanks, airplanes) and validation (ecological validation in particular) of simulated counterparts, where the former concerns things like shooting projectiles while the latter concerns generating corresponding relevant information about things like shooting projectiles.

In systems engineering laymen’s terms “validation” refers to ensuring “the right thing is done” and “verification” to ensuring “the thing is done right.” Arguably, in modeling & simulation (M&S) engineering “validation is concerned with building the right model” and “verification is concerned with building the model right” (Balci, 1994).

For training intended uses, ecological validation must ensure not only that “the right models and simulation systems” encode the right authoritative simuland referents (i.e., the right body of knowledge about the thing being simulated), but also that those models and simulation systems prompt “the right action possibilities” (i.e., the right perceived affordances) that result in “the right learning” (i.e., positive ToT).

Fidelity and Part-Task Simulation-Based Training

A primary concern of virtual simulator design-and-development in training research is to reproduce relevant experimental conditions that elicit behaviors similar to those in real-world situations (Rehman, 1995)—to avert or mitigate adverse cognitive work load, incoherent user performance parameters, and negative ToT.

Debunking assumptions that more fidelity is always better, M&S research has uncovered that effective M&S engineering involves choosing relevant aspects of referents and how much of their representational quality (e.g., accuracy, precision, resolution, sensitivity, granularity, fitness, tolerance, abstraction, detail, error) to implement (Gross, 1999; Gross, Pace, Harmon, & Tucker, 1999; Youngblood & Harmon, 2005). This is particularly true in part-task simulations where a reductionist approach is taken to examine responses to isolated function manipulations that exclude unwanted variance induced by extraneous factors.

The critical objective for part-task simulation fidelity specification is not to necessarily maximize realism but to optimize training (Bunker, 1978; Orlady et al., 1988; Rehman, 1995) in the quest to achieve positive ToT and obtain the amount of transfer desired (Kinkade & Wheaton, 1972). Thus, fidelity specifications must include physical fidelity (i.e., look and feel) as well as functional fidelity (i.e., behavior) (Allen et al., 1991) validated against simuland and affordance referents. Ecological validity and ToT assessments must strike a balance between physical and functional attributes—that have bearing on motor-skill and cognitive tasks of interest.

Context of Baseball Batting Task

“Keeping the eye on the ball” remains an elusive task for baseball players and trainers and thus presents a worthwhile case study in validation of virtual-simulation-based training. The parameters of pitched-baseballs are well known offering a stable simuland referent, and the general and adaptive properties of the oculomotor system are also well documented (Optican, 1985)—with implication to motor skill and cognitive components—thereby also providing a stable basis for an affordance referent relative to the baseball batting task.

The regulation linear distance from pitcher’s plate at the mound to the back of home plate is 60.5 ft, but approximately 55 ft when accounting for the pitcher’s point-of-release (Figure 1 A). The batter’s field of view (FOV) when tracking a pitched backspin baseball (i.e., fastball) from the pitcher’s release point to the front outside corner of home plate is approximately 40˚ (Figure 1 B). A ball traveling a simple linear path at 60-mph constant speed with no opposing forces would take approximately 625 ms to cover 55-ft, but 685 ms when accounting for parabolic path and deceleration due to the drag of air resistance—a non-trivial 10% increase in time given the nature and demands of the batting task. For instance, it has been estimated that the last pitch of Tim Lincecum's no-hitter in July 13, 2013 dropped from 84 mph to 77 mph due to drag forces (Kagan & Nathan, 2014).

From a batter's perspective, a fastball travels in-depth and slightly off-center toward the batter. This configuration presents a special case of oculomotor analysis in which the required positional angle of view (AOV) and corresponding AOV angular velocity (AOV rate of change) start very small but increase dramatically as the fastball travels its trajectory from beginning to end. The graphs in Figure 1 C illustrate the difference in required AOV and AOV rate of change for fastballs traveling both at constant 60-mph and with 60-mph initial speed but decelerating due to air drag (Bahill, 1981).

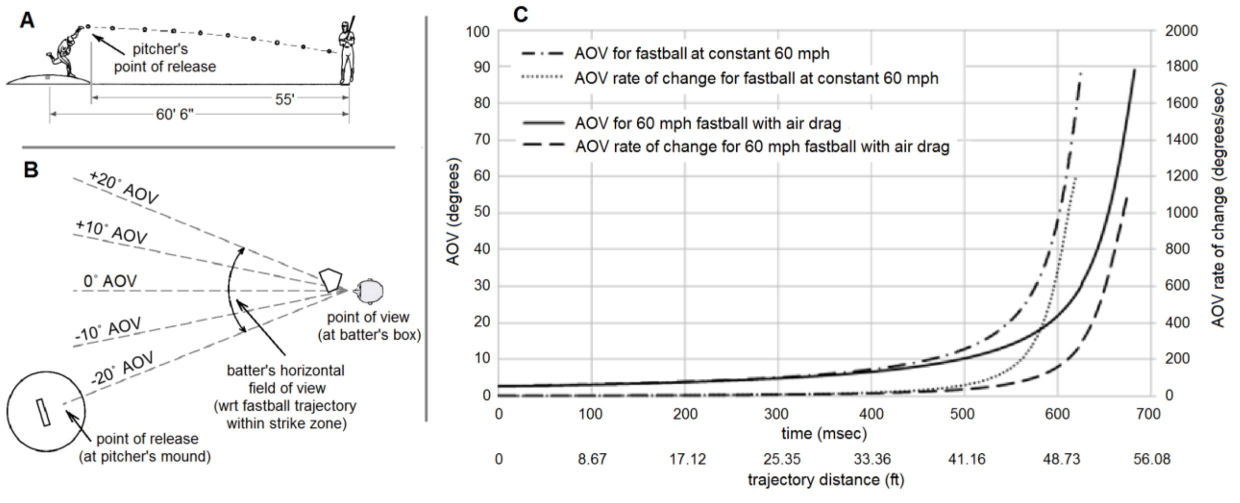

Figure 1. A. Pitched Ball Distance, B. Batter's FOV Relative to Pitched Ball Trajectory, C. Required AOV and AOV Rate of Change for Continuous Tracking of Pitched Baseball (Bahill, 1981).

Oculomotor Characteristics in Visual Orienting

The human visual system involves the oculomotor plant and neural systems that control eye movements in order to see images clearly (Enderle, 2010). Three agonist-antagonist extraocular muscle pairs and an eyeball afford five types of rotational eye movements (i.e., saccades, smooth pursuit, optokinetic, vestibular, and vergence) each controlled by a different neural system that shares the same final common pathway to the extraocular eye muscles (Enderle, 2010). In addition, ciliary muscles respond to accommodation (i.e., lens focusing) signals which are intertwined with vergence signals resulting in complementary vergence-accommodation and accommodative-vergence responses (Inoue & Ohzu, 1997; Kung, Alvarez, & Semmlow, 2003; Morgan, 1944; Schor & Kotulak, 1986).

Smooth pursuit refers to responses to position and velocity errors that foveate a relatively slow-moving object. It affords clear and uninterrupted vision but cannot be elicited voluntarily, it must be triggered by a continuous moving visual target in the field of vision. Smooth pursuit maximum velocity is 40-70^0/second (s) with approximate time delay of 100-200 millisecond (ms) after target acquisition (Enderle, 2010). Although performance depends on the quality and predictability of target movements, such that anticipatory responses may occur with little or no latency (Bahill & McDonald, 1983; Becker & Fuchs, 1985; Enderle, 2010), human smooth pursuit alone has been found to be insufficient for continuously tracking the entire trajectory of a pitched baseball in the baseball batting task (Figure 1 C) (Bahill, 1981).

Saccades are quick and jerky movements used to direct gaze from one static or moving target to another and can be elicited voluntarily even without a visual target (Enderle, 2010). They are frequently used in time-sensitive tasks as they are characterized by high accuracy and high angular velocity. However, visual processing is turned off in the course of a saccade, rendering the observer significantly blind (i.e., saccadic masking or saccadic suppression) (Enderle, 2010), therefore it is assumed that time-limited visual-search strategies that employ fewer saccades tend to be more effective since fewer fixations of longer duration enable greater extraction and processing of relevant information (Williams, Davids, & Williams, 1999). Saccades can range from a few minutes to 100^0 in amplitude with latencies from 100 to 300 ms, although those triggered by the natural environment are generally in the order of 15^0 or less (Bahill, Adler, & Stark, 1975; Enderle, 2010) in amplitude, and those in the range of 5^0 - 40^0 amplitude generally have durations and latencies both within 100 ms.

Tracking targets in the real world often involves smooth pursuit assisted by catch-up saccades (Enderle, 2010) and optimal smooth pursuit results at angular velocities of approximately 40^0/s (Schalen, 1980). It has been inferred that professional baseball batters may employ a combination of smooth pursuit, saccades, and peripheral vision to cope with the batting task (Hubbard & Seng, 1954; LaRitz, Hall, & Bahill, 1983). Given the characteristics of smooth pursuit and saccades, it may be deduced that, when tracking a 60-mph fastball, optimal smooth pursuit may occur at approximately 465 ms (i.e., slightly over two thirds of the 685 ms trajectory time) with scarcely enough time for one saccade to place the AOV near the front edge of home plate where contact with the ball would be timely.

METHOD

Participants

Five human subjects self-described as novice to experienced, 42.4 ±14.4 years old and 17.4 ±11.3 years of competitive baseball experience, participated in the exploratory study. Experimental procedures were reviewed and approved by the Old Dominion University (ODU) Institutional Review Board (IRB) and each subject gave informed consent. Participants were screened for: age (18-55 years), competitive baseball experience, visual and stereoscopic acuity, right-handed batter (or switch-hitter) without regard to eye dominance, no history of eye defects/injury or 3D-induced sickness/symptoms, and not undergoing performance enhancement or depressant medication therapies.

Dependent Variables

The principal dependent measures were the catch-up saccade onset time and amplitude derived from positional AOV in response to 60-mph live and virtual backspin fastballs with head restrained to isolate eye movements. Positional AOV measures spanned a 40˚ arc covering the initial trajectory location at assumed point-of-release to approximately 14 inches in front of the leading edge of the home plate (Figure 1 B).

Experimental Setup

A *simulation-couple* consisted of a Live-Pitch Simulation Server (LPSS) and a Virtual-Pitch Simulation Server (VPSS) counterpart, both configured in a client-server architecture and calibrated to launch/present 60-mph, 1200 rpm, back-spin, 55-ft, parabolic fastball trajectories.

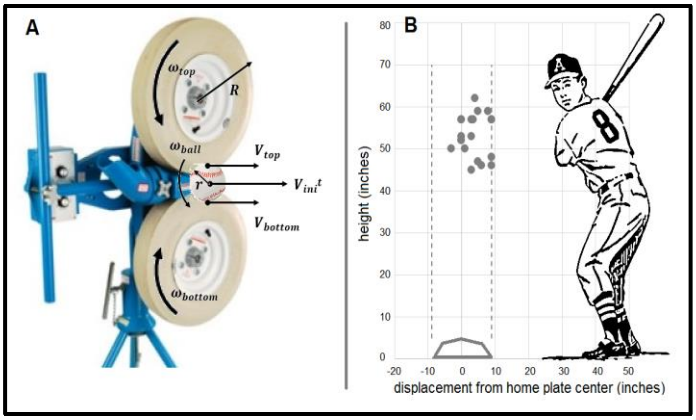

Figure 2. A. Pitching Machine with Free Body Diagram of Rotational and Tangential Velocities as Proxy for Live Pitching, B. Scatter Plot of Sample Live Fastballs.

The LPSS was a professional 2-wheel rotary (JUGS, Tualatin, OR) pitching machine (Figure 2 A) instrumented with redundant Hall Effect, photoelectric, and impact sensors to measure initial time of trajectory, rotational speed of pitching machine wheels (transferred to balls), and final time of trajectory. The calibrated LPSS produced fastballs with mean initial velocity of 60.23±2.3 mph and mean total flight time of 685.55±18.55 ms, with mean vertical height of 53.2±4.96 inches at back of home plate, and mean horizontal displacement from home plate center of 3.73±3.61 inches (Figure 2 B).

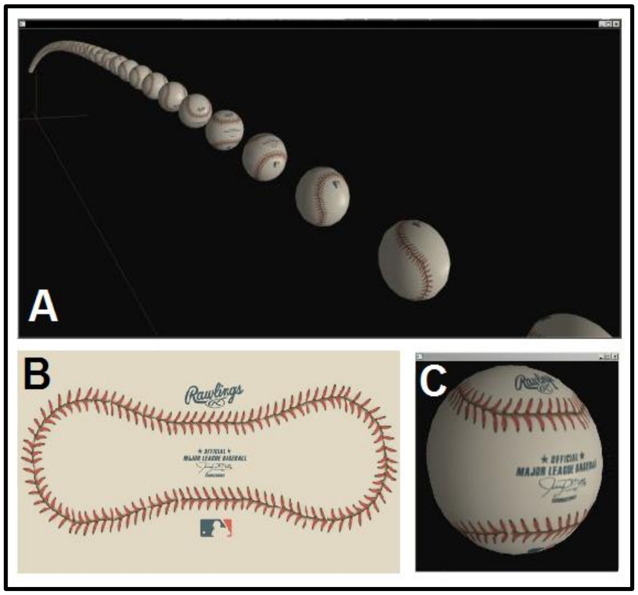

Figure 3. A. Screen Capture of Virtual Fastball Trajectory, B. Texture Map Used for Virtual Fastball Model, C. Texturized Sphere.

The VPSS was a custom-built 3D stereo virtual environment in life-size theater format with virtual fastball trajectory model, consisting of simple projectile motion with air drag/resistance deceleration (Kagan & Nathan, 2014) and ball rotation, configured to match the LPSS empirical measures (Figure 3 A). The VPSS application implemented the OpenGL mipmapping function loadMpMappedTexture() to texturize a simple sphere (Figure 3 B-C) and Off-Axis Method with non-symmetric camera frustum to render stereo pairs with independent focal points for each eye (Bourke, 1999). The virtual fastball 3D stereo configuration observed a 0.5 diopter mismatch heuristic (Merritt, 2011) with viewer distance at 7 ft to match the width of viewer display allowing batters' FOV of interest to span 40^0 with 5^0 to 10^0 of buffer space at left and right edges of display.

Eye movements were detected using a low-cost, custom-built electrooculography (EOG) system in bi-temporal "cyclopean eye" electrode configuration (Heide, Koenig, Trillenberg, Kompf, & Zee, 1999) and consisting of a Linear Technology LT1167 integrated instrumentation amplifier (Linear Technology, Milpitas, CA) and Arduino Mega ADK (Arduino, Scarmagno, Italy) microcontroller with Ethernet shield. It relied on precision and filtering capabilities native to the instrumentation amplifier and was powered by 12-volt/20-hr lead-acid batteries, encased in a grounded Faraday box with 3-wire shielded connections to mitigate ambient noise. Delays associated with transmission of stimuli and responses across the client-server architecture and with 3D projector input lag were measured and factored into participant eye-movement responses.

Measures

Oculomotor measures of horizontal smooth pursuit and saccades were obtained while participants observed live 60-mph fastballs to establish horizontal eye-movement affordance referents. Participants then observed static, continuous, step-wise, and slow-motion moving virtual targets for positional AOV calibration, nominal pursuit and saccade baseline determination, and fastball tracking threshold baselines followed by tracking performance measures of virtual 60-mph fastballs. Baselines and performance measures were preceded and followed by positional AOV calibration. In all, each participant observed 30 baseline and performance events along with 80 calibration events.

Positional AOV Calibration: Redundant positional AOV calibration measures (i.e., calibration before and after baseline and performance measures) were used for validation of EOG system accuracy as has been recommended (Heide et al., 1999) given the persistence of slow baseline drift caused primarily by the polarization of electrodes and changes in skin resistance (Heide et al., 1999), retinal potential changes due to ambient light changes (Henn, 1993), contamination from electroencephalography (EEG) and electromyography (EMG) artifacts, and other potential sources (e.g., individual physiology, non-compliance head movement, etc.) common in EOG data acquisition.

In each of the before-and-after calibration measures, participants fixated on each of five fixed targets for 3s. The targets were located directly in front of the participant (i.e., center = 0˚) and at two locations to the left and right corresponding to ±10˚ and ±20˚. For live-pitch events, the calibration targets were physically located on a perpendicular wall 20 ft away from the observer, whereas for virtual-pitch events the targets were displayed on a perpendicular screen 7 ft away from the observer. In both cases the targets were 6 ft up from the ground (i.e., approximate eye-level of fastball trajectory at terminal phase). The physical calibration targets were white disks 4 inches in diameter with 3-inch black numbers (1-5) identifying the targets (from left to right) and a half-inch dot in the middle to mitigate eye movement during target fixations. The 4-inch diameter (i.e., 1˚ eccentricity at 20 ft distance) was selected arbitrarily over the 2.865-inch baseball silhouette diameter to facilitate target location and mitigate eye-movement within central-vision eccentricity. The virtual calibration targets were baseballs of 2.865-inch baseball silhouette diameter (i.e., 2˚ eccentricity at 7ft distance).

Accuracy for each calibration angle was computed as the mean absolute error (MAE) divided by the 40˚ FOV. Calibration accuracies were generally well within 5% (i.e., 2.34%, 0.91%, 0.92%, 0.77%, and 0.94% for the -20˚, -10˚, 0˚, +10˚, and +20˚ AOVs, respectively) (Figure 4 A).

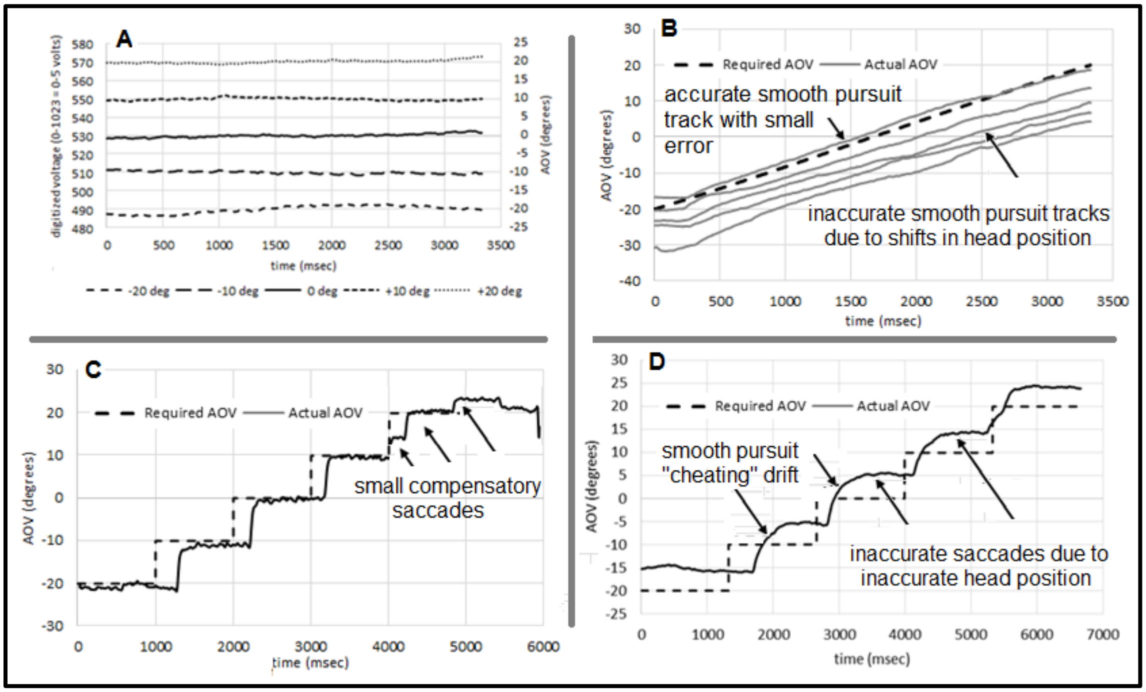

Figure 4. A. Sample Voltage to AOV Conversions of Fixed-Target Calibration, B. Sample Smooth-Pursuit/Ramp Baseline Tracks with Head Movement, C. and D. Sample Saccade/Step Baseline Tracks with Non-Compliance Drift

Smooth Pursuit/Ramp and Saccade/Step Baseline Referents: Smooth Pursuit/Ramp and Saccade/Step baseline measures were used to establish participants' nominal smooth-pursuit and saccadic ability, respectively. These baselines were also instrumental to detecting head shifts and to redundant validation of EOG system measures.

Smooth pursuit and saccade baseline determination followed paradigms used to quantify smooth pursuit (Becker & Fuchs, 1985; Schalen, 1980) and saccades (Isotalo, Lasker, & Zee, 2005; Zuber, Semmlow, & Stark, 1968) in normal subjects. For smooth pursuit, a target starting from rest at the left-most position (-20˚) moved continuously from left to right on a horizontal linear path at 12 mph requiring horizontal eye rotation of 12˚/s. For saccades, the target started from rest and moved step-wise left to right instantaneously from -20˚ to +20˚ in 10˚ increments with inter-stimulus interval (ISI) of 1300 ms. Each participant observed five smooth pursuit and five saccade baseline events.

Representative baselines of smooth-pursuit/ramp and saccade/step responses (with head movement, drift, and participant non-compliance error) are presented in (Figure 4 B-C-D). Positional accuracy for ramp and step baselines was computed similar to positional AOV calibration; ramp baselines were within 5% (e.g., 3.08% for Figure 4 B), step baselines were within 10% (e.g., 6.93% for Figure 4 C). Difference in ramp and step positional accuracies were due to latencies at saccade onset (200-280 ms; typical saccade latency is approximately 100 ms (Enderle, 2010)).

Fastball-Tracking Threshold Baseline Referents: Fastball-tracking threshold measures were intended to provide more-accurate insights into participants' fastball velocity sensitivity, beyond simply whether or not a batter could keep up with a 60-mph fastball, and more revealing of the upper velocity limit when tracking ability begins to fail. These baselines were particularly insightful to validation of oculomotor affordances—particularly as pertaining to potential sensitivity measures of impaired accommodative-vergence resulting from 3D stereo displays.

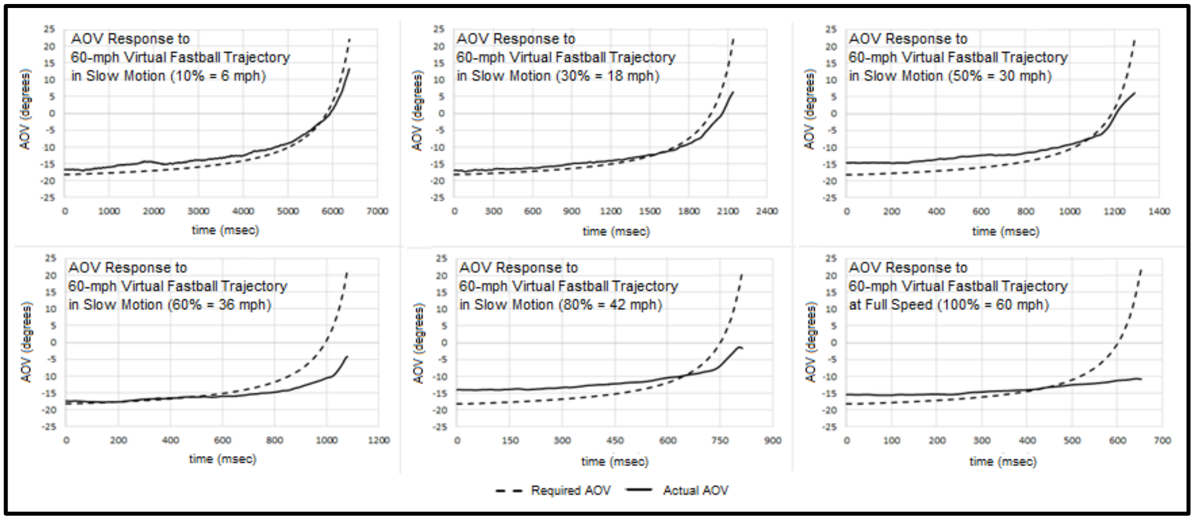

Figure 5. Representative Slow-Motion Threshold Baseline Tracks.

Fastball-tracking baseline determination consisted of participant-tracking of virtual 60-mph fastballs presented in slow motion speeds in 10% increments from 10% to 100% of the 60-mph target fastball speed (i.e., 6 mph to 60 mph in 10 mph increments). The slow-motion trajectories preserved and controlled for the spatial geometry accuracy of true full-speed 60-mph fastballs. Each participant observed 10 threshold baseline events.

The 60-mph fastball trajectory at various slow-motion speeds was tracked (Figure 5). Visual inspection of these baselines reveals smooth-pursuit positional AOV error is small at 10% of full speed but increases as early as 30% of full speed. Positional error increased at a greater rate beyond the 50% slow-motion speed, inducing saccade responses.

Live Fastball Tracking Affordance Referents: Fastball-tracking affordance referents consisted of fastball-tracking performance measures while participants observed one set of five live fastballs.

Virtual Fastball-Tracking Performance: Virtual fastball-tracking performance consisted of response measures to one set of five virtual 60-mph fastballs following the same protocol as the fastball-tracking affordance referent measures.

Data Processing

Savitzky–Golay (S-G) smoothing (Savitsky & Golay, 1964) was used to improve signal-to-noise ratio of EOG recordings (e.g., Figure 6 A). Data was sampled at approximately 3266 Hz and resampled at 3100 Hz to obtain consistent equispaced data sets amenable to normalization and analysis as has been done elsewhere (Fan & Lin, 1998). The redundant pre- and post-calibration runs (e.g., Figure 6 B-C) were translated into an EOG baseline drift reference (e.g., Figure 6 D) used for conversion of measured retinal potentials (EOG voltages) to positional AOV degrees using simple linear interpolation. The EOG baseline drift was near-linear across the 40˚ working FOV for ~3 minutes.

Data Analysis

Angular velocity was derived from positional AOV. Least-squares analysis was used to fit an Exponentially Modified Gaussian (equation 1) (Golubev, 2017) to saccade velocity curves and derive the sum of squares (SS), residual sum of squares (SSE), and coefficient of determination (R^2). The Exponentially Modified Gaussian model was selected based on its similarity of asymmetry and skewness against saccade characteristics (Van Opstal & Van Gisbergen, 1987). The model was fitted to the experimental saccadic measures and used for performance analysis (e.g., Figure 7 A and B).

$$f(t;\, \mu,\sigma,\lambda) = \frac{\lambda}{2} + e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2t)} erfc(\frac{\mu+\lambda\sigma^2-t}{\sqrt{2}\sigma}) \qquad (1)$$

t = time, μ and σ = mean and variance of Gaussian, λ = rate of exponential, erfc = complementary error function

“Main Sequence” analysis was used to derive saccade onset times, amplitudes, and duration from the Exponentially Modified Gaussian model. It was assumed general saccade onset is characterized by velocities of at least 30^0- 40^0/s sustained for a minimum of 30 ms (Baloh, Sills, Kumley, & Honrubia, 1975; Lin, Chen, Chen, & Tsai, 2004) and general maximum velocity of smooth pursuit in the order of 50^0- 70^0/s (Enderle, 2010) with optimal smooth pursuit angular velocities of approximately 40^0/s (Schalen, 1980). Main Sequence saccade analysis is based on near-linear relationship between amplitude and duration and near-exponential relationship between amplitude and maximum velocity (Bahill, Clark, & Stark, 1975; Baloh et al., 1975; Boghen, Troost, Daroff, Dell'Osso, & Birkett, 1974; Lin et al., 2004; Van Opstal & Van Gisbergen, 1987). The main-sequence analysis was conducted beyond the 400-ms time period which corresponds to the terminal phase of the fastball trajectory where transitions from smooth pursuit to catch-up saccades are more likely to take place.

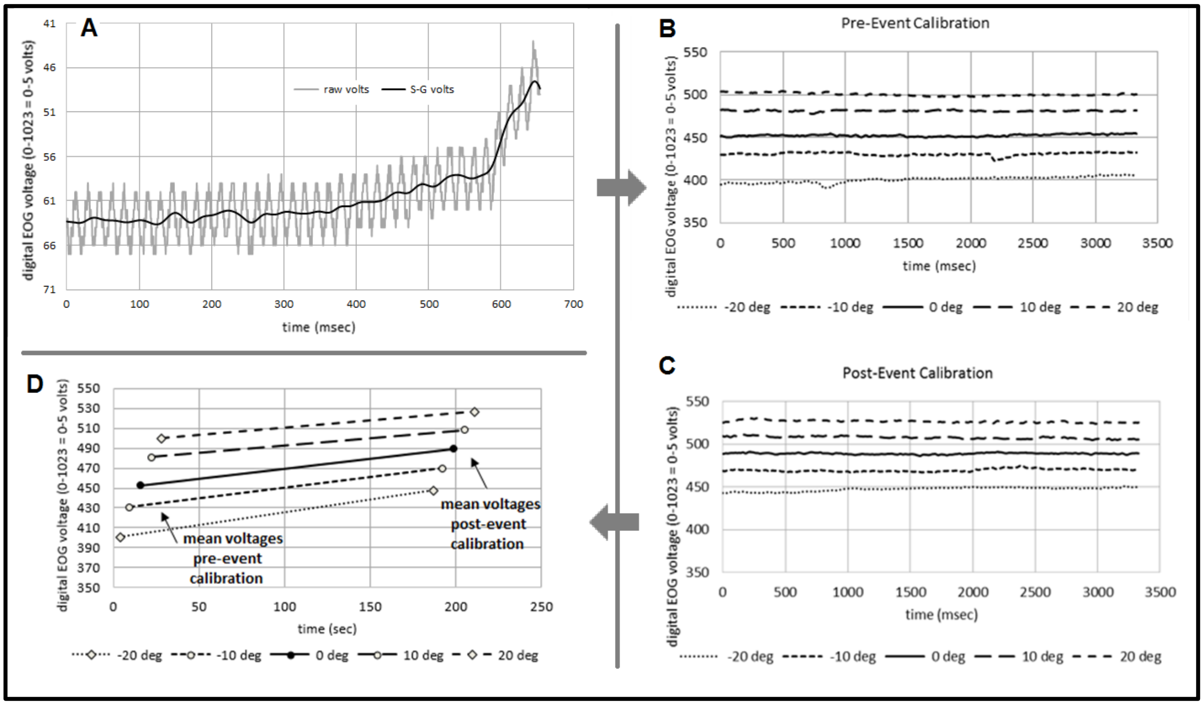

Figure 6. A. Sample Raw EOG Signal Processed with Savitsky-Golay Digital Filter, B. and C. Sample Pre- and Post-Event Calibration Recordings Showing EOG Baseline Drift, D. Sample Baseline Drift Reference.

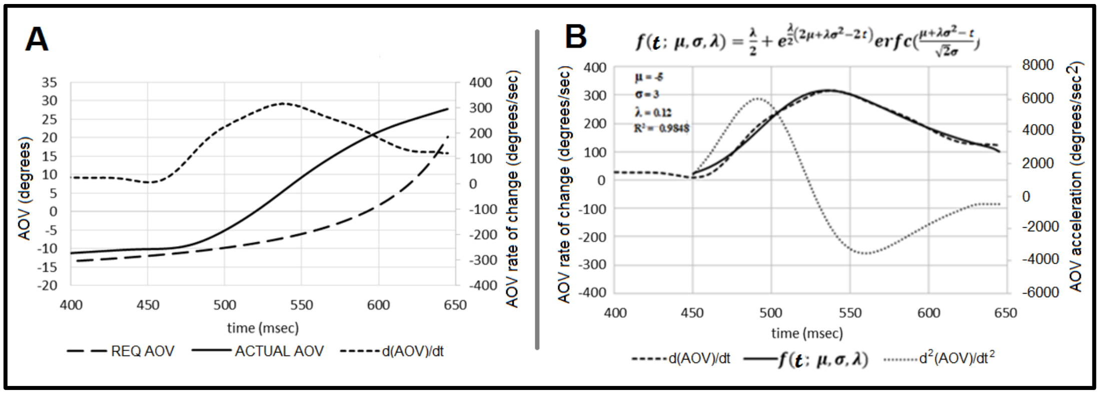

Figure 7. A-Sample Saccade Response to Virtual Fastball, B-Saccade-Fitted Exponentially Modified Gaussian.

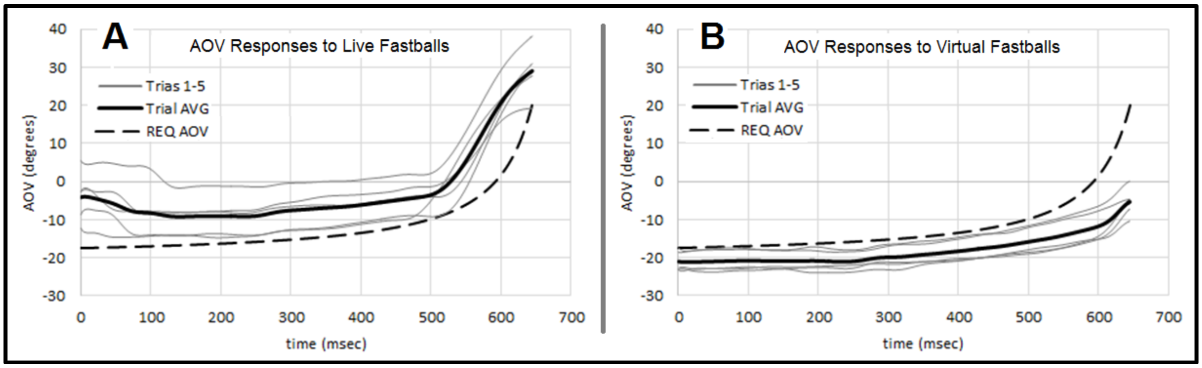

Figure 8. Representative AOV Responses to Live and Virtual Fastballs.

Table 1. Mean Saccade Onset Times (ms) for 60-mph Live and Virtual Fastballs

Participant	**001**	**003**	**004**	**013**	**015**	**AVG**
Experience	Experienced	Novice	Experienced	Experienced	Novice	
Live	448.59±41.39	536.52±35.16	493.5 ±49.41	447.82±49.77	509.26±32.48	**487.1±41.64**
Virtual	580.88±18.64	529.29±45.08	543.24±45.31	551.88±45.58	578.67±9.18	**556.79±32.76**
Diff of Means	+132.29	-7.23	+49.74	+104.06	+69.41	**+69.69**

Table 2. Mean Saccade Amplitudes (degrees) for 60-mph Fastballs

Participant	**001**	**003**	**004**	**013**	**015**	**AVG**
Experience	Experienced	Novice	Experienced	Experienced	Novice	
Live	32.29±6.72	15.81±15.33	15.43±10.72	24.49±23.23	25.50±7.25	**22.70±12.65**
Virtual	12.55±6.75	6.21±3.66	6.01±2.46	4.85±2.50	5.71±1.32	**7.07±3.34**
Diff of Means	-19.74	-9.6	-9.42	-19.64	-19.79	**-15.63**

RESULTS

Positional AOV provided the basis for velocity, acceleration, and other response measures. Saccade onset time was selected as a reasonable marker for determining smooth pursuit to saccade transitions. Saccade half-amplitude was estimated conservatively from saccade onset to peak velocity; full amplitude could not be measured directly since the limited 40˚ FOV did not allow a consistent and definitive AOV corresponding to fastball end-state.

Representative AOV responses to live and virtual fastballs (Figure 8) reveal consistent responses within live-pitch trials and within virtual-pitch trials (albeit with some head-movement shifts) but inconsistent responses across live and virtual trials. Responses to virtual pitches appeared more accurate (i.e., on target) and precise (i.e., less variation) in the early phase of the trajectory but also uncharacteristically flat, non-erratic, and steady throughout the trajectory. They were also characterized by late catch-up saccades beyond 400 ms of the fastball trajectory with average delays in the order of 70 ms greater than responses to live fastballs. Saccade amplitudes for virtual fastballs were on average approximately 15˚ smaller than those for live fastballs, but the amplitude estimates were inconclusive since a definitive velocity peak could not be determined given the limited 40˚ FOV and corresponding eye-movement recording.

Table 1 and Table 2 summarize mean saccade onset times and amplitudes in response to live and virtual responses across more and less experienced batters. These results indicate that live fastballs elicited saccade responses near the smooth-pursuit maximum velocity threshold (400-500 ms) among more experienced batters and slower responses (>

500 ms) among novice batters. The response to live fastballs also appears to have elicited some type of defensive head/eye movements (i.e., flinching) at the beginning of the trajectory, up to approximately 100 ms. These initial corrective eye movements were likely an adjustment to the initial acquisition of the ball (i.e., the ball was not visible prior to emerging from the pitching-machine shoot) and stabilized on target approximately 200-300 ms prior to the 400-500 ms pursuit-saccade transition period.

DISCUSSION

The aim of this exploratory pilot study was to gain clinical insights and evidence into the important role of affordance referents in ecological validation of virtual-simulation trainers. The pilot data generated from this first-of-a-kind study should serve future design of simulation-based experiments by providing estimates of effect size for statistical power calculations. A challenge to consider, as it was in this study, would be to administer a sufficient but not excessive number of live and virtual fastballs (or other type of pitches) without inducing a Practice Effect (Newell & Rosenbloom, 1980) resulting from repeated testing.

This study was unique in that it addressed a special case of oculomotor analysis not previously covered in baseball batting performance or virtual-simulation ecological validation analysis. That is, extensive research has been conducted on conjugate eye movements involving targets on horizontal planes moving laterally at fixed distances, and some involving targets moving in-depth directly centered on the observer but the batting task presents a special case of oculomotor analysis because a fastball travels in-depth but slightly off-center toward the batter, requiring positional AOV and AOV rate of change starting very small but increasing dramatically.

Baseball tracking in the batting task has been studied in the contexts of smooth-pursuit tolerance, pitch-type determination, and other criteria. Studies have employed mechanical simulations using plastic balls attached to fishing lines and propelled by falling counterweights or by electric motors, or various types of desktop or 2D theater-format virtual simulations devoid of valid kinematics (e.g., projectile motion due to gravity, ball rotation, air drag) (Bahill, 1981; Hyllegard, 1991; Shank & Haywood, 1987). This study was the first to include valid kinematics and air drag.

The study revealed that variability in saccade onset time responses across more- and less-experienced participants suggests not only that experience and habit may influence responses differently (as might be expected) but also that responses to live and virtual fastballs are processed differently, offering insights into ecological validation strategies for virtual simulation trainers.

The slower saccade onset times resulting from virtual fastballs (~70 ms or ~13% compared to live fastballs) may be attributable in part (30-40 ms) to system delays (i.e., projector and client-server message lag times) but such delays do not explain flat responses lacking gradual curvature as compared to responses to live fastballs or slow-motion virtual fastball baselines. The 120 Hz display rate may cause perceived discontinuities toward the end of the trajectory, but these should precipitate a saccade trigger rather than delay its onset. Trajectory occlusion discontinuities have been examined as enablers of saccade trigger with mixed results (Roca, 2016) and should be examined further.

Some of the remaining difference in saccade onset delays may be attributable to accommodative-vergence impairment induced by the fixed focal plane of 3D stereo displays and should be examined further (analysis of accommodative-vergence was outside the scope of this study). Smooth pursuit thresholds and transitions to saccades in the context of the baseball batting task have not been explored sufficiently, especially involving 3D stereo graphics stimuli in which eye-movement convergence/divergence takes place, but accommodation does not. Gaze depth has been found to respond to target depth under stereoscopic conditions (Duchowski, 2011) but it has not been explicitly measured under the demanding batting task conditions. Further examination of accommodative-vergence in 3D stereo virtual simulation would be valuable not only to characterize its influence on eye-movement affordances and corresponding ecological validity of simulated environments in 3D stereo but also in the contexts of a possible non-invasive alternative to isolation and characterization of accommodation and vergence signals and of analysis of stereo blindness or of 3D stereo perception in the absence of measurable stereo acuity (Tidbury, Black, & O'Connor, 2014).

Future work will build on these and other findings with simulation-couple paradigm to explore training protocols using incremental rehearsal and partial occlusion (Roca, 2016) as well as to accumulate saccade onset affordance referents relative to more extensive expert and novice performance, different fastball speeds, types of pitches (e.g., curve balls, sliders), and player categories (e.g., age, gender, experience, eye dominance, etc.) among other variables.

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