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THESIS

VISUAL FIELD REQUIREMENTS FOR PRECISION NAP-OF-THE-EARTH HELICOPTER FLIGHT

by

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September, 2002

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13. ABSTRACT

Helicopter flight simulation visuals must display terrain for high altitude flights as well as flights within a few feet of the terrain. Currently high altitude visuals are well understood and supported, but extremely low altitude visuals are not. Terrain relief and texturing that appears convincing at high altitudes is drastically oversimplified at NOE altitudes, eliminating critical visual cues. Without adequate visual cues, simulated NOE flight is pointless, or worse, may induce negative training transfer. Too much visual complexity will overburden a real-time 3D graphics pipeline adversely affecting frame rate and usability. This thesis attempts to identify the minimal visual requirement for NOE helicopter simulation, thus enabling future simulator and trainer designers to make informed decisions regarding design criteria tradeoffs.

Based on a task analysis of hovering over an unprepared landing site, critical cues were implemented in a fixed base helicopter flight simulator and tested on ten military helicopter pilots. Results indicate that a critical density of visually complex three-dimensional vegetation in combination with high-resolution terrain textures enabled experienced military helicopter pilots to accurately determine helicopter motion and make control corrections. Hover performance was degraded using lower vegetation densities and significantly degraded using just high-resolution textures.

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VISUAL FIELD REQUIREMENTS FOR PRECISION NAP-OF-THE-EARTH HELICOPTER FLIGHT

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I. INTRODUCTION

A. PROBLEM STATEMENT AND MOTIVATION

The task of precisely hovering a helicopter at extremely low altitudes requires great skill acquired over many practice missions. The task is all the more critical as it is typically carried out for combat personnel transfer under hostile threat conditions in terrain that prevents a landing. Improper control inputs can lead to personnel injury or a helicopter crash in a span of seconds. Currently, the only way to practice this skill is in the aircraft in the real world. This is both costly and somewhat dangerous at times, further limiting opportunities to train. Current simulators do not adequately provide the required cues to allow an experienced helicopter pilot to use real world procedures and techniques, so pilots "game the sim"[1] or avoid simulator training at low altitudes altogether. This limits the role of a simulator to basic procedures training in relatively benign surroundings and prevents its use as an effective cognitive tactical training device.

To be successful as a cognitive tactical trainer, a simulator should not force a pilot to learn a new simulator specific way to fly. Thus, task critical cues need to be reproduced in a manner that allows pilots to make decisions and react in a manner as similar to the real world as possible. Split-second tactical decisions made in a virtual environment that has a significantly different set of critical cues (not cue appearance) from the real world have limited applicability and the virtual environment would need to undergo extensive evaluation to ensure negative training was not taking place, let alone verify any positive training transfer to real world operations. A virtual environment configured to support these types of low altitude hovering tasks will be a significant step towards creating a true cognitive tactical training device that can positively impact real world tactical training safety and combat effectiveness.

[1] To "game the sim" means to figure out a way to accomplish a task in the simulator even though the method is inappropriate for real world task performance.

B. RESEARCH QUESTION

This thesis concentrates on one of the most basic questions that needs to be answered to successfully implement an effective low altitude helicopter simulation: What is the minimum level of visual detail required to maintain a steady, precise, hover in a helicopter flight simulation? A low altitude hover task analysis will identify the actual real world cues used in hovering and will be used to provide guidance as to what cues should be implemented into a simulation. Further study and experimentation will attempt to quantify the required density of the included cues in the simulation.

C. ORGANIZATION OF THESIS

This thesis is organized into the following chapters:

Chapter I: Introduction. This chapter includes an introduction to the problem, motivation and outline for this thesis.

Chapter II: Background. This chapter contains pertinent background information, including a task analysis, which defines the critical cues necessary for the hovering task.

Chapter III: Simulator Implementation. This chapter describes the hardware and software specifications required to support the experimental framework and details the components used to implement the specifications.

Chapter IV: Methodology. This chapter details the experimental protocols and conduct.

Chapter V: Experimental Results. This chapter evaluates the data and reports the results from the experiment.

Chapter VI: Conclusions and Future Work. This chapter contains the conclusions reached from the experimental process and describes research concepts/ implementation details that the author was unable to accomplish due to time and/or technology constraints.

II. BACKGROUND

A. TASK ANALYSIS FOR A H-60, DAY, VMC, LOW HOVER AND IDENTIFICATION OF TASK CRITICAL CUES

1. Introduction

This task analysis is specifically derived from flying the Sikorsky H-60, but is representative of any passenger carrying helicopter. Terminology differences may occur between specific helicopter models, but the basic functionality of those items is relatively consistent. The one exception to this is in the H-60's doppler hover display instrumentation, but the difference is mitigated by limitations resulting in non-use of the display for a precision daytime hover.

2. Decision Making Framework

The decision making process of an experienced helicopter pilot during the hovering task very closely adheres to the Recognition-Primed Decision (RPD) Model illustrated in Figure 1 [1]. Flight conditions are assessed and matched against the pilots experience base and appropriate control inputs are matched, then executed via muscle memory, all without an exhaustive search of options. With experience, the process is essentially automatic. The specific flight regime of a low hover itself is not greatly different than a normal hover, but the precision required for troop transfer operations via a Jacobs Ladder, or hovering over a pinnacle/ledge with a single wheel in ground contact reduces the positioning tolerance from plus-or-minus feet, to plus-or-minus inches. To successfully control the helicopter within these tolerances, the available cues must be unambiguous and allow the decision/action cycle of deviation detection and control input to proceed as rapidly as possible.

Given appropriate, unambiguous cues the pilot will match a drift rate, magnitude and inferred cause against prior experience to determine if a typical situation exists as illustrated in Figure 1 Level 1. If the cues are ambiguous or inadequate, precious time is wasted in the diagnosis phase illustrated in Figure 1 Level 2. Time relegated to diagnosis is time not spent with an appropriate control input applied, leading to an unstable hover position. Once a typical situation has been recognized there are four by-products, three of which are useful in the short-fused cycle times available: (1) Expectancies of future events or actions, this primes the pump for the next decision point and narrows the tasks scope, helping to accelerate future decisions, (2) Highlighting relevant cues, this reduces the search time in future cue acquisition and may initiate searches for new cues, such as a persistent drift in one direction may prompt the pilot to assess potential wind direction changes, (3) Typical action, the appropriate control input, (4) Plausible goals, this by-product is not particularly useful as the consistent overarching goal is a precise hover at a fixed point in space and subordinate goals are the helicopter movements required to regain that position. The matched course of action is implemented via muscle memory and an evaluation of the resulting situation is made starting the cycle over again. Evaluation and mental simulation illustrated in Level 3 of Figure 1 is not used in the tight decision/action control loop.

The RPD model fits well, but alone does not provide us with the requisite tools or information to identify the critical components missing from current simulators and virtual Environments. A formal task analysis tying the decisions actions and cues together is required.

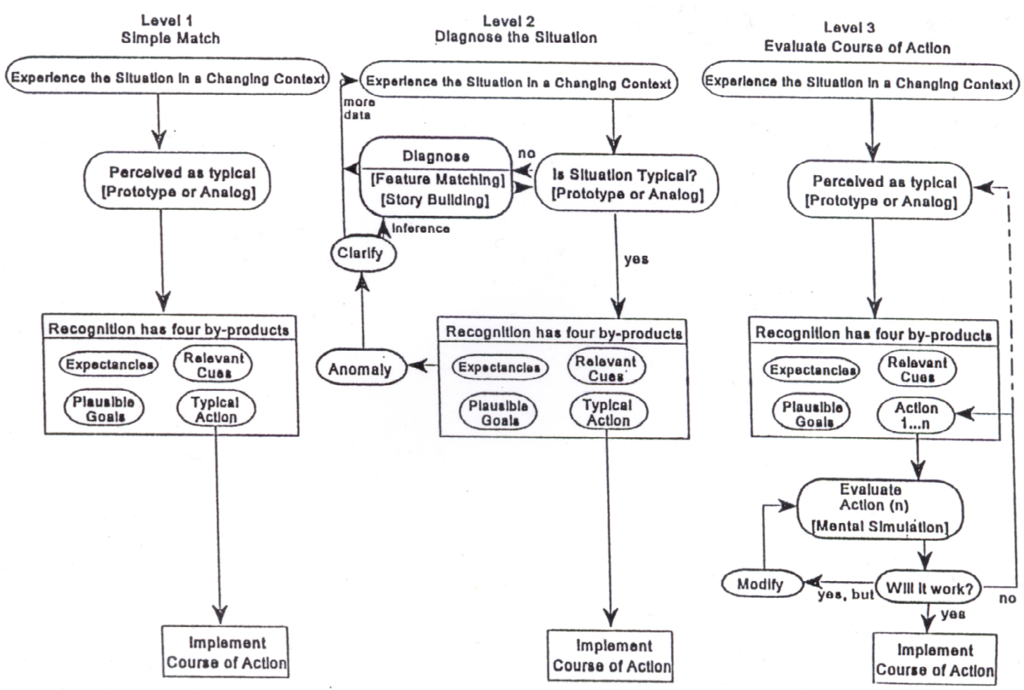

Figure 1 Recognition-Primed Decision Model [1]

3. A GOMS Model of Low Altitude Hovering

The GOMS Model methodology [2] is applied to draw out the details of the hovering, exposing the critical cues used to successfully accomplish the task. The basic model has a structure consisting of four components: (1) Goals, (2) Operators, (3) Methods for achieving the goals and (4) Selection Rules for choosing among competing methods. The modeling methodology assumes the process proceeds serially accomplishing one goal at a time. This is not necessarily the case in the hovering task, but if we make the assumption that sequential, serially completed, decision/action loops are accomplished rapidly enough, the end effect is indistinguishable from the result of parallelized operations. This assumption is not objectionable here as we are primarily concerned with the information (cues) required to make the decision, not the inner-workings of the cognitive process itself. Separating the procedure into individual components that are rapidly completed in serial fashion also relieves the requirement to explicitly code all cue permutations.

The overall goal of hovering the helicopter is broken down into component **unit-tasks**, which are goals themselves. The mechanics of GOMS break the **unit-tasks** into sub-goals of **acquire** and **execute.** The mechanics of **acquire** lead to a series of **get** statements, which are responsible for driving the tasks decision/action cycle. In this model the **get** statements correspond to execution tasks that are again expressed as **goals**. These **get/goal** pairs are nested to the same depth in the fully formed model described in Figure 2. The lowest level in this model is the separation of the cue driven **select**ion within the DETERMINE **goal** from the action **select**ed to satisfy the **get/goal** pair.

Goals. Goals describe the hierarchy of tasks and sub-task relationships. Dots are a visual aid to represent the nesting level within the model.

GOAL: LOW ALTITUDE HOVER (LAH)

The chosen complex task is described within the model as the highest level goal.

GOAL: LOW ALTITUDE HOVER (LAH)
• GOAL: LAH-UNIT-TASK
• • GOAL: LAH-ACQUIRE-UNIT-TASK ***repeat until departing hover***
• • • GET-DRIFT-CORRECTION
• • • GET-HEADING-CORRECTION
• • • GET-ALTITUDE-CORRECTION
• • GOAL: LAH-EXECUTE-UNIT-TASK
• • • GOAL: CORRECT-DRIFT-DEVIATION
• • • • GOAL: DETERMINE DIRECTION / MAGNITUDE
• • • • • [select USE FLIGHT INSTRUMENT HSVD DOPPLER
USE PERIPHERAL METHOD
USE FIXED REFERENCE METHOD
USE CREW TALK-OVER METHOD
USE SPATIAL OCCLUSION METHOD
• • • • [select USE-LONG TERM CORRECTION METHOD
USE-SHORT TERM CORRECTION METHOD
USE-TRANSIENT CORRECTION METHOD
• • • GOAL: CORRECT-ALTITUDE-DEVIATION
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USE CREW TALK-OVER METHOD
USE SPATIAL OCCLUSION METHOD
USE FLIGHT INST. HSVD HEADING INDICATOR
USE FIXED REFERENCE METHOD
• • • • [select USE-LONG TERM CORRECTION METHOD
USE-SHORT TERM CORRECTION METHOD
USE-TRANSIENT CORRECTION METHOD

Figure 2 A GOMS Model for a Low Altitude Hover

. GOAL: LAH-UNIT-TASK

All complex tasks are comprised of smaller unit tasks, this goal formalizes the concept within this model.

. . GOAL: LAH-ACQUIRE-UNIT-TASK

This goal continuously drives the decision / action loop at the high level of determining whether or not a unit-task correction method is required to be executed. If one of the nested get operators returns a positional deviation, the associated execute-unit-task goal is fired. When the appropriate use method has been selected and initiated, control is returned to the acquire-unit-task goal and the cycle continues.

. . GOAL: LAH-EXECUTE-UNIT-TASK

The sub-goals of this goal are invoked via the firing of get operators nested within the acquire-unit-task goal. The execute-unit-task goal itself has no direct effects within the model, it exists as the placeholder partner to acquire-unit-task and ensure the three following **CORRECT** goals are consistently nested with the get operators.

. . . GOAL: CORRECT-DRIFT-DEVIATION

. . . GOAL: CORRECT-ALTITUDE-DEVIATION

. . . GOAL: CORRECT-HEADING-DEVIATION

These three goals entail the meat of the hovering task, returning the helicopter to the desired hover position. Drift is defined here as lateral or longitudinal displacement and associated motion, altitude and heading deviation are self-explanatory. The process these three goals drive is a tight cycle of determining the direction and magnitude of any displacement followed by selection of a method to correct the discrepancy. The determination sub-goal and correction method select blocks are nested at the same depth within the **CORRECT** goal blocks and ordered explicitly indicating the means to achieve the goal.

. . . . GOAL: DETERMINE DIR. / MAGNITUDE

This is a common sub-goal across the three **CORRECT** goals above. This goal simply encodes the need to determine the movement vector direction and magnitude prior to choosing a course of action. The ordering of use methods / selection rules in the **SELECT** block following this goal roughly signifies the precision and therefore utility of the method from least to most precise. There will be variability in which method is selected due to personal experience, preference, skill-level and cue types available. Despite the fact this goal is a sub-goal to the three different **CORRECT** goals presented above, and the specific reason a cue is examined changes between goals, the process remains the same and so a single uniform representation is made.

Get Operators. Each get operator fires in turn and invokes the corresponding **CORRECT** goal within the execute-unit-task goal.

. . . GET-DRIFT-CORRECTION

. . . GET-HEADING-CORRECTION

. . . GET-ALTITUDE-CORRECTION

If there is a measurable deviation from the desired hover position the **CORRECT** goal executes to completion and returns control to the next get operator. If there is no measurable deviation, control is returned immediately. A sufficiently rapid looping through the get operators will minimize deviation magnitudes.

Use Methods / Selection Rules. There are two types of use methods in this model, cueing and action. Cueing methods are the palate the pilot has at their disposal to determine deviations from the desired hover position and any associated motions that must be corrected as well. The first eight use methods described here are cueing methods for identifying deviations and the remaining three are action methods used to correct the deviations once detected. Note, there is no continuous monitoring of a single actions result. Rather than maintain a list of active actions and determine when each should be terminated, the model invokes an action as a one time positioning of the flight controls, leaving future get operators to invoke actions that work as counter-corrections. This implementation holds up better in high pilot workload situations than a model that requires memory and continuous evaluation of an arbitrary number of previously implemented actions.

USE PERIPHERAL METHOD

Peripheral vision provides motion cues on a long, medium, and sometimes short term basis. The peripheral motion is not only sensed out of the sides of the eyes, but very often also out the upper or lower portions of the vision field. The horizontal periphery will pick out two-dimensional horizontal drift, while the upper and lower periphery is quite good at recognizing angular changes in heading. Peripheral sensitivity to motion is very great, but quantification of motion magnitude is not as precise. Small magnitude drift motion is also somewhat susceptible to washout by noise introduced in transient helicopter attitude changes. Overall the peripheral cues normally provide the pilot excellent information to determine moderate flight control inputs, which will result in a new centroid for future control inputs. Virtually any nearby object large enough and with enough contrast to stand out as an individual object within the peripheral field of view is usable for this method.

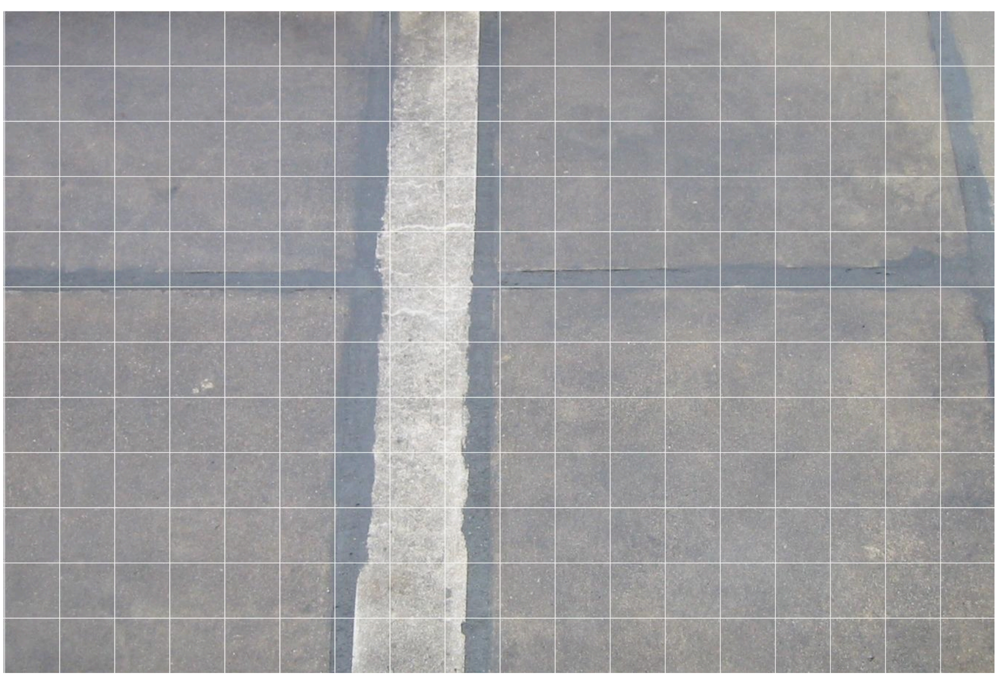


Figure 3 Peripheral and Fixed Reference Cues, #a

USE FIXED REFERENCE METHOD

Judging relative motion against an easily distinguishable object and holding its relative position constant in the field of view is the standard method for hover positioning. Using a steady eye-position and cross referencing the exterior object against a fixed internal reference frame such as a canopy bow or glare screen support can further refine the positioning information. Objects need not be large, well defined gravel embedded in tarmac can be effective in this method. Lateral and longitudinal drift, and heading, are controlled quite effectively using these cues. The main weakness is precise altitude control. Changes in relative object size due to altitude changes are not immediately apparent, even as the object is maintained steady in the field of view.

Figure 3 - Figure 8, illustrate the advantages and disadvantages of peripheral and fixed reference cues. Although these photographs are not panoramic and fully representational of peripheral vision, they do a credible job of illustrating the differences in the portion of the peripheral visual field that will have the greatest impact on deviation determination. The original photographs were cropped to eliminate background clutter and have a grid superimposed to better highlight differences between frames.

Figure 4 Peripheral and Fixed Reference Cues, #b

Consider Figure 3 as the baseline visual field the pilot desires to maintain in an effort to keep the hover position steady. Use the boundaries of the photo as imaginary canopy bows for a fixed internal reference. Figure 4 is a result of a slide three feet to the right. The displacement of the concrete joints is quite obvious and the motion of an object with the size and contrast of the white stripe is noticed readily in the periphery. Contrast the ease of deviation detection between Figure 3 & Figure 4 with Figure 5 & Figure 6.

Figure 5 Peripheral and Fixed Reference Cues, #c

Figure 6 Peripheral and Fixed Reference Cues, #d

At first glance comparing Figure 5 and Figure 6, there it isn't an obvious difference that stands out. The actual displacement was three feet forward and three feet right from Figure 5 to Figure 6. If the pilot was looking continuously at this scene the motion cues would stand out, although magnitude cues are not easily discernable. Had the motion taken place during a cockpit distraction or internal scan, it would be very difficult to notice the subtle differences. This would be an excellent time to augment the positioning information with talk-over cues presented later in this section.

Figure 7 Peripheral and Fixed Reference Cues, #e

Figure 7 illustrates much the same information as Figure 4, but with a change in heading vice positional drift. Now, imagine a turbulent gust of wind jostling the helicopter that results in the sight picture from Figure 8.

What is the deviation from Figure 7 to Figure 8? From the original hover position established in Figure 3? From Figure 7, heading has been restored with a left turn and altitude has increased by approximately one foot. A Three-foot left slide is required to restore the helicopter to its starting position, Figure 3. While the one foot altitude change seems like a negligible difference, it is at or just beyond the positional tolerance for a one-wheel hover, or a substantial difference for a soldier while mounting a Jacobs Ladder for embarkation.

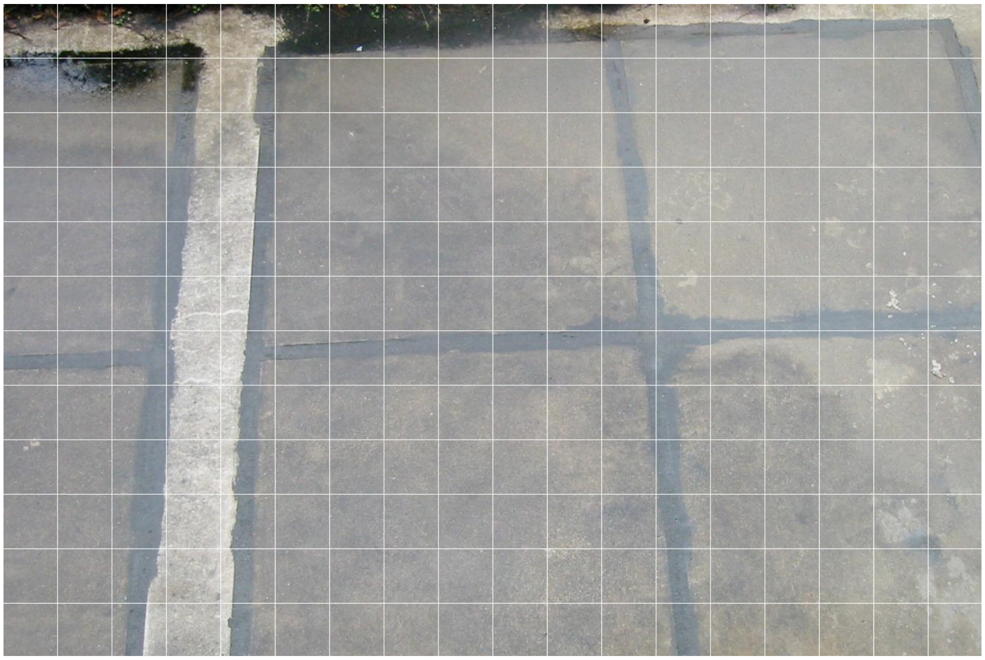


Figure 8 Peripheral and Fixed Reference Cues, #f

USE SPATIAL OCCLUSION METHOD

This method is a refinement or adaptation of the **FIXED REFERENCE METHOD** and supports extremely precise positional cues. Objects that are relatively unaffected by the rotor downwash and remain stable may be used as a fixed reference point and three-dimensional motion judged very finely by background motion against the fixed foreground reference. The method is not optimal for determining magnitude of large positional differences, but is best used to catch small deviations and determine corrections very quickly. Many desert plants or rock formations exhibit enough resistance to motion in rotor downwash as well as many man made objects such as fences or wreckage. Spatial occlusion alone is not particularly effective for heading control as fuselage rotations may occur while maintaining a fixed eye location.

Consider Figure 9 as the baseline visual field the pilot desires to maintain in an effort to keep the hover position steady. Note the relationships of various objects in the scene. The trash bin and central leaf cluster orientation are two of the easier relationships to compare. This plant was chosen because it is quite stiff and would maintain its configuration quite well in rotor downwash, it also exhibited enough variation in all three dimensions to create immediately obvious motion cues with as little as a plus-or-minus three inch side to side and/or up/down head motion. The whole plant has surfaces that changed shape or cross in front of other surfaces creating a localized motion field out of the occlusions. The trash bin in the background illustrates how the motion effect is magnified with a longer visual lever-arm, moving the bin in and out of view due to relatively small differences in observer position.

Figure 9 Occlusion Motion Cues, #a

The trash bin in Figure 10 is an excellent cue as it has gone out of sight behind the plants in the background. The foreground plant now seems to be leaning towards the right and the leaves in the lower front occlude more of the central cluster than they did before as well as having more visible lower surfaces. Had video footage been presented rather than just two photographs the motion of one foot down and to the left would have been very obvious.

Figure 10 Occlusion Motion Cues, #b

USE CREW TALK-OVER METHOD

Verbal positioning commands given by crewmembers looking out the cargo door are very valuable for positioning the helicopter in relation to an object the pilot cannot see. Once the desired hover position is reached, the pilots should obtain an independent reference for continued positioning cues, as the communication time delays injected in the process will eventually lead to over control and temporary loss of a precise hover position unless anchored by that independent reference. The crewmember continues to monitor the helicopters position in relation to the desired point and only provides positioning information as required. The positioning calls require direction, magnitude and relative rate information for optimal control, allowing some pilot anticipation for counter-corrections to null out motion induced intentionally. Crew talk-over alone provides good positioning information, but in combination with fixed reference or spatial occlusion methods, exceptionally precise helicopter positioning can be accomplished and maintained for significant periods of time.

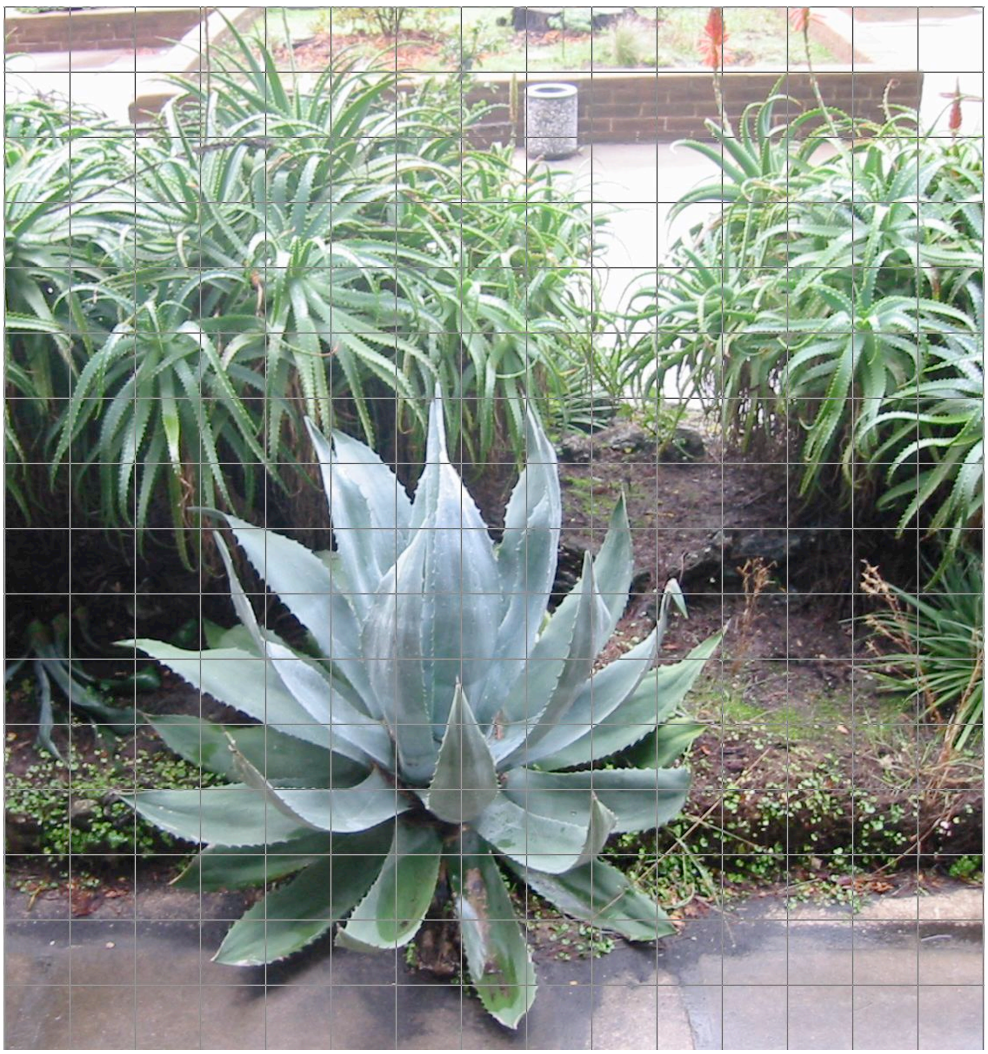
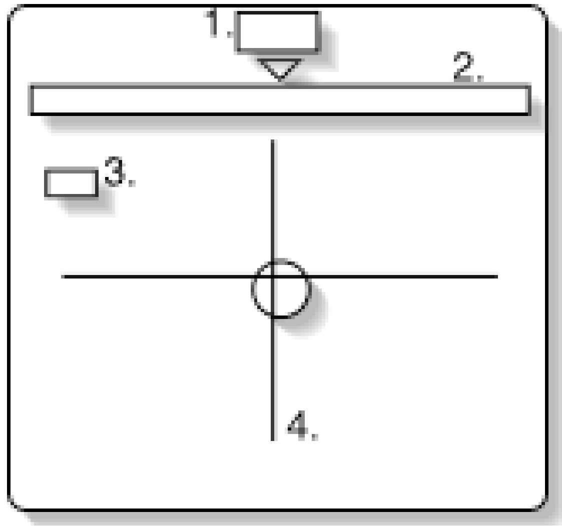


Figure 11 Occlusion Motion Cues, #c

What motion results in the view depicted Figure 11? An eighteen inch slide to the right, from the observer position in Figure 10.

USE FLIGHT INSTRUMENT HSVD HEADING INDICATOR



1. Digital heading display
2. Heading tape
3. Digital altitude display
4. Doppler drift bars and central 10 knot magnitude circle

Figure 12 Simplified Horizontal Situation Video Display

The H-60 HSVD provides the pilot with a plethora of information, see Figure 12 for a very simplified layout. There are two readouts of aircraft heading, a pure digital number readout and a heading tape display. Sensitivity of the digital readout is very good and only cycles or flips as the heading reaches half-degree areas, useful information itself. The tape display is very good as a quick reference, displaying major tic-marks at ten-degree intervals and minor marks at five-degree intervals. This information can be assimilated concurrently with HSVD drift assessment and altitude information, but as the HSVD drift information is not well suited to precision day hovers (there is a six-second integration delay in the displayed drift information, and it is difficult to mentally extract rate-of-change information from the display) the information co-location is not a significant advantage for a precision hover. The main drawback of this method, although minor, is the requirement to scan inside the cockpit diverting attention from other external positioning methods. If used as part of a well-executed scan it can be a good cueing system for a day overland precision hover.

USE FLIGHT INSTRUMENT RADALT INDICATOR

The H-60 radar altimeter analog display gauge provides the pilot with a pointer-based readout of absolute aircraft wheel height. Sensitivity of the system is exceptional and the analog display is immune to numeric cycling, which reduces usability of the digital altitude display in the Horizontal Situation Video Display (HSVD). Determining altitude rate-of-change and deviation of the pointer from large tic-marked ten foot increments is very intuitive, judging five foot intervals between the large tic-marks is not much more difficult, even without an explicit tic-mark. Maintaining position on one of the minor two-foot interior tic-marks takes more mental effort and time in the scan process. The main drawback of this method, although minor, is the requirement to scan inside the cockpit diverting attention from other positioning methods. If used as part of a well-executed scan it can be a good cueing system for a day overland precision hover.

USE FLIGHT INSTRUMENT HSVD RADALT

The H-60 HSVD also provides the pilot with a digital readout of absolute radar altimeter altitude. Sensitivity of the system is not optimized for single digit accuracy and the units-digit cycles or flips almost constantly. Although this information can be assimilated concurrently with drift assessment and heading information, the cycling effect makes this a low precision cueing system for a day overland precision hover.

USE FLIGHT INSTRUMENT HSVD DOPPLER

The H-60 HSVD doppler hover mode provides the pilot with a head in the cockpit reference for drift direction and magnitude. As the helicopter drifts horizontal and vertical deviation bars move presenting a fly-to cue for the pilot. The pilot manipulates the flight controls to move the helicopter towards the intersection point of the deviation bars and maintain a long term goal of having the bars intersect coincident with the fixed center tic-marks. Due to doppler system integration times, the deviation bars representations lag actual motion by six seconds. This factor makes the HSVD doppler hover display a very low priority cueing system for a day overland precision hover.

USE-LONG TERM CORRECTION

This correction yields a new control position centroid as a basic start point for all future control inputs. Commonly the pilot will make a rough correction with force-trim (see *III.A.2.b)* for detailed explanation of force-trim) released and re-engage force trim at the estimated position for the new control centroid. This may be refined over a small number of deviation assessment / control input cycles. Perceived reasons for making control inputs affect the decision just as much as the magnitude of the correction. Persistent shifts in local winds require long-term corrections while highly variable shifty conditions may favor a series of short-term corrections. Apparent wind cues outside the area affected by rotor downwash provide much of the information required for the long term vs. short-term decisions. Without visual cues of wind direction and magnitude, the process of determining long term corrections is much more difficult and hovers tend to be more positionally unstable as a repeated short term corrections are required. The difference between long term correction refinement and a short-term correction is normally the intent to use and use of force-trim to establish the new control centroid, reducing workload for future control short term and transient correction inputs.

USE-SHORT TERM CORRECTION

This correction compensates for a deviation without the need to establish a new control position centroid. Short term corrections are typically made opposite of, and in response to, small drift rates and magnitudes thereby preventing magnitudes from reaching a point where a long term correction may be required. The control inputs are commonly made against the force-trim allowing the controls to return to the centroid upon release of the short-term input. Highly experienced and proficient pilots will have an extremely rapid drift determination/correction cycles that require very small control inputs. Short-term corrections are normally differentiated from transient corrections in the length of time the input is held and motivation for the control input. These inputs are nearly always drift related and applied for some number of seconds, as opposed to input and immediate removal.

USE-TRANSIENT CORRECTION

This correction normally compensates for helicopter attitude disturbances or as a counter-correction to terminate a short or long term correction's induced motion. In the case of attitude disturbances these corrections are typically made before a drift rate develops, anticipating drift created by helicopter attitude excursions generated by turbulent airflow. These inputs are mainly cued by seat-of-the-pants attitude determinations that come with significant aircraft experience. As the corrections are made before a drift rate actually builds to a detectable level, they are almost always small and immediately removed, much the same as the turbulence driven attitude changing forces themselves are extremely short lived. These corrections alter helicopter attitude but generally cause no easily discernable longitudinal, lateral or vertical motion of the helicopter

4. Discussion

The detail encapsulated within the GOMS model **use** methods very directly illustrates the type of cues that allow a pilot to successfully perform the low altitude hovering task: 1) peripheral, 2) fixed-reference, 3) occluding, 4) talk-over and 5) flight instruments. This particular task is not an every flight occurrence, but every flight does pass through the same low altitude on landing and takeoff. An environment rich enough to permit natural performance of the advanced hovering task should also support other advanced tasks within the NOE flight environment where the helicopter literally flies between trees and bushes, or unprepared surface landings where the helicopter could land on any flat open area that is large enough.

It should be quite obvious by this point that flat textured terrain is not adequate for precision or tactical helicopter flight, even if the textures are exquisitely detailed (reference Figure 5 & Figure 6 ground cover). While simulated flight is readily accomplished without the cues described herein, the resulting techniques applied in some critical phases of flight are artificial simulator only techniques and lead to questions of negative training or at the very least, reduced training transfer to real world operations.

B. SUMMARY OF PREVIOUS RESEARCH

Vection, peripheral vision, field-of-view, immersion, simulator sickness and motion are all intrinsically linked in a flight simulation of any fidelity. Each design factor must be balanced within a trainer to yield the maximum training transfer. Immersion and the sense of presence, traditionally high on the list of goals in VE construction are by-products of sound design, not ends in and of themselves. Among the many design criteria for a helicopter tactics trainer in the NOE flight regime, two have traditionally been thought of as diametrically opposed: natural/precise visual motion determination and minimization of simulator sickness. Many of the individual elements required to visually generate precise motion determination have been labeled as problematic and prime contributors in generating simulator sickness. The below synopsis of related work identifies factors considered in the hardware and software design for this thesis experiment and contests some early conclusions on specific simulator sickness contributing factors.

Vection is the illusory sense of continuous movement in a particular direction even though the body remains relatively stationary. This virtual movement has been well documented as being highly influenced by peripheral vision including a recent study by Lowther & Ware [3]. There is also ample research confirming the phenomenon at the basic psycho-physical level which directly supports the role of peripheral vision in motion determination and orientation, including it's role in conveying information to the brain without requiring explicit attention, Chen, Fortes, Klatzky & Long [4] & Money [5]. More practically, widescreen visuals have been employed as an immersive tool in the cinema industry since the 1950's in a attempt to give the illusion of physical presence, above and beyond the normal "suspension of disbelief" crafted by darkened theaters, sound and the viewers enjoyment of the film as reported by Hedges [6]. The cinema industry discovered through audience testing that widescreen projection creates a subjective sense of movement with the camera for the viewer. The formally defined constructs of optical flow and visual displacement are responsible for this sense of movement and are enhanced when more of the presented image is onto the peripheral vision field. This intrinsic human dependence on peripheral vision makes it highly desirable to incorporate widescreen peripheral displays in a flight trainer that attempts to recreate the critical cues helicopter pilots naturally use in NOE flight.

Optic flow is an abstract sensation with no absolute reference, explored by von der Heyde, Riecke, Cunningham & Bülthoff [7], where the continuous visual displacement of contrasting areas is mentally integrated into a direction and rate of travel. While highly useful in determining motion direction and rate, optic flow is lacking as a definitive cue for precision magnitude determinations. The experiments of Chen et.al.[7] and von der Heyde & Bülthoff [8] conducted on motion through a VE compared the uses of pure optic flow and more concrete displacement cues (visual landmarks) as a guidance mode for turns. It was found that while subjects primarily used landmarks when they were available and adequate for the task at hand, often those cues were not close enough for accurate judgment of the turns requiring a balanced use of the cues [8]. This makes choosing the not only the correct types of cues critical, but also choosing how dense those cues should be in the visual field. The use of three dimensional objects in the scene can serve double duty as both displacement landmarks and peripheral optic flow cues, all augmented by texturing on the ground planes for continuous optic flow cueing and accurate representation of the area to be flown.

There does not seem to be any currently published research on how much of these optic flow and displacement cues are "enough" for use as a precision navigation cue. The above mentioned studies tend to concentrate on the cues overall effects and relative weights, but are completed in substantially abstract virtual environments, except for [8] which used a simple virtual city as the visual landmarks for basic turning. Control of three dimensional helicopter motion is a far more complex task than any of these earlier studies attempted, but the basic psycho-physical requirements are similar enough to use as guiding precedents.

The prevalent notion that a wide field-of-view (FOV) is significant factor in causing simulator sickness dates back to research done in the relative infancy of visual systems. Early military flight simulators were a fertile proving ground for these theories with the applicable research being summarized in 1992 by Pausch, Crea & Conway [9]. As display systems technology has progressed, the focus on FOV itself as a cause for simulator sickness has not held up to actual research. The wide FOV head mounted display experiments conducted by Arthur [10] broke the perceived correlation of simulator sickness with FOV. Webb and Griffin [11] have also recently shown that wide FOV and vection is not a primary cause of simulator sickness, but that simulator sickness is more influenced by central vision than peripheral vision. This appears to identify the base causes of simulator sickness as more purely visual quality, latency and/or motion driven than has been surmised in the past. With FOV an peripheral vision removed as primary culprits in creating simulator sickness we are free to explore and implement wide field of view displays as an immersive tool without fear of automatically incurring a simulator sickness penalty.

The case for whether or not to incorporate motion into a flight simulator is not so easily resolved though. Several sources including Longridge, Bürki-Cohen, Go & Kendra [12], and Schroeder of NASA Ames Research Center [13] state motion is a critical component in improving pilot performance of tasks that equate to those used in NOE hovers, but motion itself may not materially add to training transfer of tasks performed in a simulator [12]. The experiments conducted in the Vertical Motion Simulator at NASA Ames surprisingly showed linear vertical and lateral motion components were substantially more compelling to helicopter pilots in hovering tasks than the pitch and roll components. Pilots were also able to accomplish more precise control of a hover with the linear motions than when only pitch and roll motions were present, making it altogether possible that traditional six degree of freedom triangulated motion bases do not provide the correct motion cues for helicopter hovering operations [13]. Therefore by not incorporating motion into this simulator, some degradation in ability to completely and faithfully recreate some fine flying tasks such as hovering and NOE maneuvers can be expected, but those physical degradations would likely not affect the cognitive level training tasks of a tactical trainer as long as they do not present a significant distraction to the pilot.

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III. SIMULATOR IMPLEMENTATION

A. REQUIREMENTS

The driving force of this thesis is the experimental aim of defining low altitude visual requirements for future helicopter tactical trainers. A secondary consideration was creating the hardware and software framework, which can be extended in future work and ultimately refined into a deployable trainer. This simulator implementation is a requirement validation platform first, and a deployable flight trainer proof-of-concept second. Requirements directly associated with this thesis' experiment will be discussed in detail and secondary considerations will be noted as required.

1. Systems Requirements

a) System Classification

The system should be unclassified in its basic procedures training configuration, allowing unrestricted use by personnel and no special location requirements. Should real world mission rehearsal be desired, modularity and design should be adequate to allow the system to be used with databases of arbitrary classification in less than five minutes reconfiguration time.

b) Commodity Hardware

Commodity commercial hardware should be used to the maximum extent practicable. Computer hardware, especially graphics hardware is advancing at phenomenal rates with current commodity equipment outperforming 3-5 year old custom, dedicated graphics workstations at costs an order of magnitude less or more! Commodity hardware will be much more easily replaced and maintained when damaged or inoperative, and commodity pricing will enable short-term upgrade cycles. Upgrading commodity PCs can vastly increase capability with minimal to non-existent requirements for software changes. Despite the fact commodity PCs should be used, these machines should not be subject to the IT-21 Standard as they are not intended for use as general computing systems, but specifically purposed as dedicated trainer hardware.

Visual display solutions have not currently evolved enough to fully become commodity items, but any display system should connect via industry standard connectors to a commodity PC graphics accelerator card.

Commercially available, USB interface, generic helicopter flight controls are available and should be used. Currently force-gradient trim is not available on commercially available PC flight simulator controls. The full impact of this must be examined in future work to determine whether or not modified or custom hardware is required.

c) Footprint

Footprint should be minimized to the maximum extent possible. The choice of display system is the primary factor here. With a head-mounted display and a sourceless tracker, it should be possible to maintain a footprint of 3’ x 6’ or less. Deployability requires maximum packaged component weights of 150 lbs and dimensions that will fit through standard shipboard watertight hatches.

2. Interface Requirements

a) Administration/Ease of Use

The system should be intuitive to set-up and use. Set-up following a trainer move should be restricted to plug and play of well-labeled components. Using the trainer should be as easy as single-point power-up, starting an application, sitting in the seat and donning a head-mounted display (if used). No special skills should be required for maintenance, administration or performing upgrades of commodity PC hardware. Ease of use is a major component in how often a trainer is used, a difficult to use trainer will sit idle or worse, left in the box.

b) Capable of Natural Flight Context

The overall goal of the individual interface requirements is to produce a mental context of helicopter flight sufficiently similar to real world flight that the cognitive decision training competed in the trainer transfers as seamlessly into the real world as possible. The context should guard against too much similarity to a particular aircraft though in an attempt to avoid direct mental mappings to a specific aircraft, which trainers such as this can never adequately match. Intentionally providing generic interface components which have appropriate helicopter-like characteristics that are acceptable to experienced helicopter pilots should allow pilots of all experience levels to conduct cognitive training without falling into a trap of negative training transfer due to physical inaccuracies to a particular aircraft.

It is critically important for a cognitive trainer not to teach trainees how to conduct stick and rudder skills, but to teach when those maneuvers may be required. This distinction makes a tactical trainer a cost benefit multiplier for high-fidelity simulator and real world training sorties. Given an adequately small footprint for deployability, it also helps address the current tactical proficiency declines during deployed periods away from adequate training ranges.

c) Visual

Visuals must support the critical cues noted in the task analysis presented in Chapter II. Three-dimensional objects are a requirement for any occlusion based cues, adequate ultra-high detailed texturing or three dimensional objects are required to enable fixed reference based cues. A major visual component that must be reinforced is a wide field-of-view. Peripheral vision is a significant component in motion determination and critical in the helicopter low altitude maneuvering regime, with peripheral cues used constantly for both gross drift and heading determinations. Without adequate peripheral cues the natural daytime hovering task is substantially deprived of the information required to execute it.

Frame rates must remain above 30 fps. Visual stuttering was very noticeable below 25 fps during early equipment testing. The physics model driving the visuals must have an update frequency greater than or equal to twice the frame rate (Nyquist frequency) or predictive motion will be required in the visuals. Avoiding predictive positioning for the cockpit visuals should be a priority as it induces control motion to flight visual motion latency of at least one frame's refresh time in milliseconds. Eliminating as much latency as possible will also reduce some of the potential sensory-cue mismatches, which are components of simulator sickness according to cue-conflict theory as described in [14].

d) Instrumentation

Even for a visually based task such as NOE flight or hovering, some flight instrumentation is required. Minimums should include a heading indicator, radar altimeter, airspeed indicator and an attitude indicator. These instruments are routinely used as cross-checks during NOE maneuvering and their absence would impart extra artificialities that would require adaptation of real world techniques into simulator specific techniques. For follow on implementations that fully support the full helicopter flight envelope, a barometric altimeter and vertical speed indicator will be required. Consideration may be given to implementing turn and slip indicators as well, but these begin to tend towards fine control feedback instruments and may reinforce physical motor control too heavily, breaking the paradigm of cognitive training.

B. HARDWARE

1. Systems Implementations and Considerations

The system block diagram is presented in Figure 13.

a) System Classification

All hardware used to implement the basic trainer platform is unclassified. Location is constrained by the use of a fixed, large, wide-screen rear projection system for the visual display, a choice that was made to use existing on-hand assets for proof-of-concept testing. Future iterations should explore display alternatives that enhance portability and minimize footprint. The overall design is modular and loosely coupled, allowing future substitutions with minimum effort or difficulty as long as interface is consistent. This should allow laptop hardware or hard drive swaps for classified mission operations in minutes. Other hardware will be unaffected and remain unclassified upon removal of the classified components.

b) Commodity Hardware

All hardware used is commercially available and the majority is considered commodity hardware.

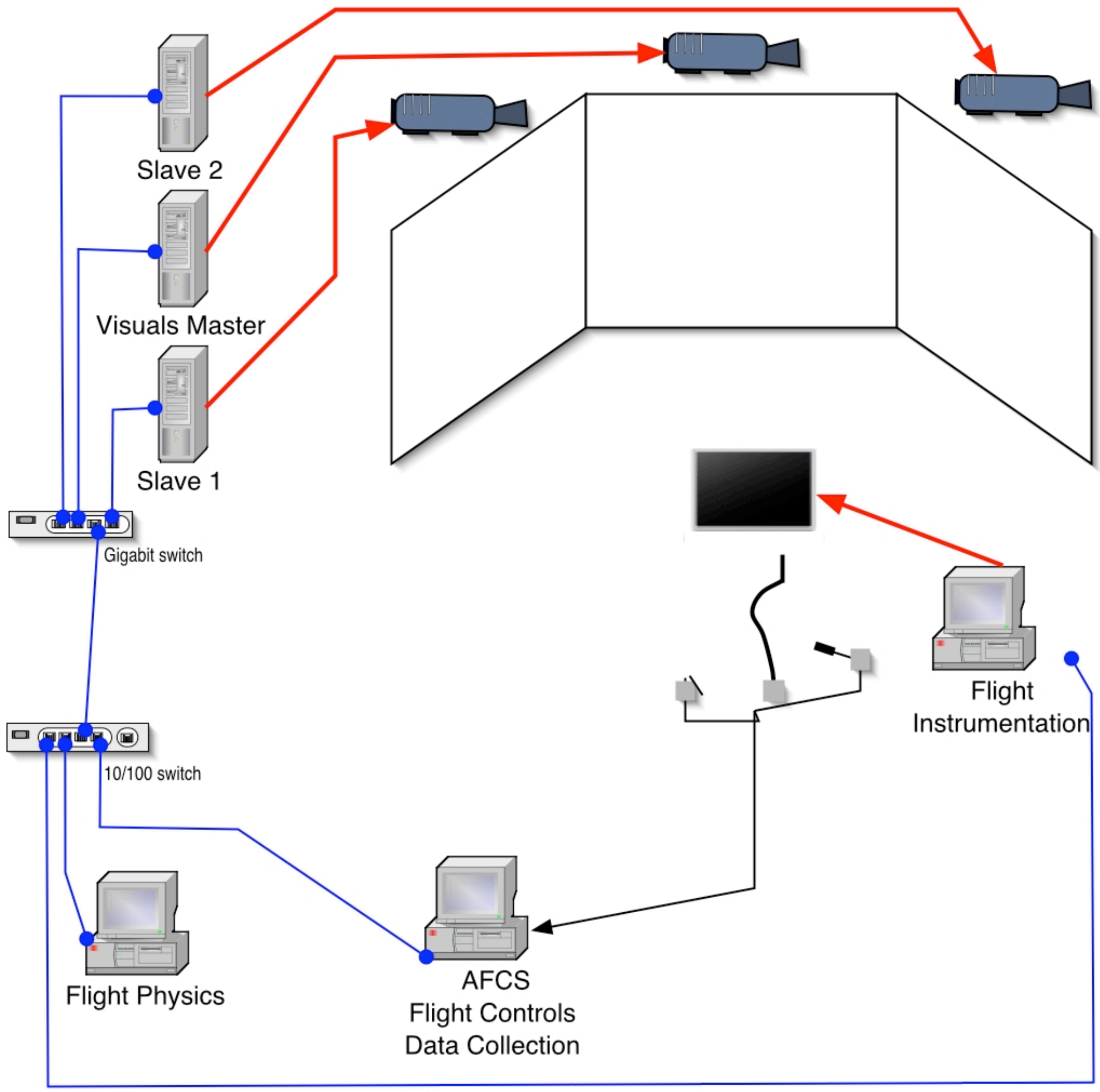

Figure 13 Hardware Block Diagram

The flight model runs on a Pentium 4, 1.3Ghz machine with 128MB of RAM, an Nvidia GeForce2MX graphics card and a 10/100BaseT Ethernet network interface card (NIC). All visual rendering options are set to minimum fidelity on the flight model, allowing a consistent 60-62 Hz update rate (max rate as throttled by software). It conducts two-way UDP/IP communication exclusively with the data collection and flight control interface computer via a 10/100BaseT switch.

The data collection and flight control interface runs on a Pentium 4, 1.7Ghz machine with 512MB of RAM, an Nvidia GeForce3 graphics card, Creative SoundBlaster Live card (for the game port) and a 10/100BaseT NIC. The flight controls are connected via the game port and all manufactured by Flight Link, Inc., G-Stick II helicopter cyclic, Collective (non-twist throttle), and Anti-Torque Pedals. It is highly recommended that future work use the G-Stick II Plus helicopter cyclic (or an equivalent), this updates the interface to USB and adds a four-way hat switch enabling the addition of beeper-trim to the control model. The data collection and flight control interface computer conducts two-way UDP/IP communication to the flight model computer and one way transmission only UDP/IP communication with the flight instruments computer via a 10/100BaseT switch and the Master visual display system computer via a 10/100BaseT switch and uplink into a 1000BaseT switch.

The flight instruments are rendered by on a Pentium III Dual 500Mhz machine with 256MB of RAM, proprietary onboard graphics chipset and a 10/100BaseT NIC. It displays the flight instruments on an SGI 1600sw LCD. The flight instrument interface computer receives one-way UDP/IP communications from the data collection and flight control interface computer via a 10/100BaseT switch.

Visuals are rendered on three Pentium III Dual 1.0Ghz machines with 1.0GB of RAM, Nvidia GeForce3 graphics cards and 10/100/1000BaseT Ethernet NICs. The three computers are set up in a master/slave configuration via software described in Section C and connected via a dedicated 1000BaseT switch. Pilot eye-point information is provided by the data collection and flight control interface computer to the Master via the uplink port on the 1000BaseT switch.

c) Commercial or Open Source Software

Commercially available or open source software should be used to the maximum extent practicable. With computer hardware, especially graphics hardware advancing at phenomenal rates, attempting to maintain and expand feature sets matching available hardware will be expensive and time consuming. Leveraging the efforts of commercial and/or open source providers will lower lifetime software support costs and allow more resources to be applied to advancing the state of training and mission rehearsal databases.

d) Footprint

Footprint of the seat, flight controls and flight instrument display is approximately 30” x 6’ and sits on a raised platform to accommodate the configuration of the existing rear-projection display system, the raised platform itself is not inherently necessary for future implementations. Total footprint of the hardware as implemented is large, but contained within the existing dedicated 20’ x 20’ room for the rear-projection display system. No effort was made to reduce footprint, as this proof-of-concept and visual requirements evaluation implementation was not designed for portability. Future implementations should leverage component modularity to reduce footprint.

2. Interface Implementations and Considerations

a) Administration/Ease of Use

This was not a design consideration for this implementation.

b) Capable of Natural Flight Context

Hardware choices and overall system implementations were made with the goal of generating believable generic helicopter flight as judged by experienced military helicopter pilots. Limitations in the current hardware and software implementations prevented a flight model representation of a fully capable military helicopter, but did closely model hovering with military-quality automatic stabilization systems inoperative.

Automated Flight Control Stabilization (AFCS) systems are robust advanced systems designed to significantly reduce pilot workload, enabling the helicopter to be more effectively employed as a weapons system. While different acronyms may be applied to this type of system for other helicopter models, the goal remains the same, stabilize an inherently unstable helicopter with the minimal pilot workload possible. With the AFCS systems facilitating a relatively stable fuselage attitude/heading the pilot can concentrate on control inputs affecting position, not maintaining aircraft stability.

Trim is an important tool for the pilot to affect both the desired attitude (via beeper-trim) and reset control loadings on the cyclic (via force-gradient trim). The flight controls used for this implementation were not capable of either type of trim input, substantially limiting the pilot's ability to stabilize the simulated helicopter and largely shifted the pilot's attention from positioning, to manual stabilization. The implemented configuration of the cyclic actually resembles a case of stuck force-gradient trim, a condition that causes the helicopter to act even more unstable than it inherently is due to the spring loaded re-centering action of the cyclic driving the flight controls away from the desired re-center position. This situation can be manually overridden, but requires significant pilot workload and constant control input. In comparison a pilot with a force-trim enabled cyclic can reset the control loading to re-center the cyclic to the desired re-center position, allowing very small and short term inputs to be made from a common starting point. The lack of force-gradient trim can also be overcome by the pilot's use of beeper-trim to set the re-center position. Beeper trim requires a four-way hat switch mounted on the cyclic. The Flight Link, Inc. G-Stick II Plus helicopter cyclic has a functional four-way hat switch and would be the preferred workaround solution for future implementations.

Even with the difficulties presented by the flight model stability, pilots that have flown the simulator accept its instability as normal behavior when they are briefed the simulated helicopter has a damaged or inoperative stabilization system. This is actually a positive indication, showing the physics of the flight model are believably appropriate for hovering tasks. Addition of appropriate AFCS functionality should be undertaken in future implementations with the expectation of much improved positional precision in hovering tasks and other low altitude maneuvers. Once the added precision meets pilot expectations, the trainer should be ready for a training transfer assessment.

c) Visual

The visual display is a three-screen rear projection display system with the outer screens set at a 45 degree offset to the central screen. Each display screen is 7' x 5' and has a fixed resolution of 1024x768 with a 60 Hz refresh provided by a VRex VR2210 projector connected to a Nvidia GF3 graphics card. From the visual "sweet-spot", six feet equidistant from all three screens, the user has a 180 degree horizontal and 43 degree vertical field-of-view.

d) Instrumentation

The flight instruments are displayed on a SGI 1600sw LCD (17.1" widescreen) with 1600x1024 resolution and 60 Hz refresh rate. This provides adequate screen real estate to display six realistically sized flight instruments.

C. SOFTWARE

1. Systems Implementations and Considerations

a) System Classification

All software used to implement the basic trainer platform is unclassified. The overall design is modular and loosely coupled, allowing future substitutions with minimum effort or difficulty as long as interface is consistent. Unless a classified flight model is implemented all software code should remain unclassified. Use of classified databases should not affect the unclassified nature of the simulation software code itself.

b) Commercial or Open Source Software

Commercial and open source software packages were used wherever possible to maximize time coding in areas where solutions were not otherwise available. All PCs used in the experiment ran under the Microsoft Windows2000 operating system. The software employed to render the virtual environment was Vega, by Multigen-Paradigm, primarily chosen for its ability to synchronize visuals across multiple displays using the Distributed Vega add-in module.

The flight physics are output from a commercial PC flight simulation, X-Plane, by Laminar Research. X-Plane was chosen mainly for its network interface which has complete coverage flight parameters via UDP/IP. This includes all required positional and angular output (including rate) information required to use for viewpoint calculations and future AFCS calculations. It also accepts input for nearly any parameter that is output, including flight control positions and trim settings. Collective-to-yaw flight control coupling (a standard helicopter flight control mechanical-mixing property) has already been implemented using these available hooks with significant success in reducing wild heading gyrations previously associated with collective changes. Attempts to implement an attitude hold function have been made, but the earlier mentioned hardware limitations with respect to trim have interfered, preventing an effective implementation. Future AFCS functionality will be significantly easier to code with the addition of hat-switch controlled trim.

A very important secondary factor in the choice of X-Plane is that the simulations internal flight modeling is accomplished via finite-element analysis, a real-time capability only recently available outside super-computing centers. Finite-element analysis applies physical laws against parameterized sub-components of the aircraft and sums the resulting forces, which are integrated into aircraft motion. Coupled with the included helper application Plane Maker, rapid first approximation for aircraft implementations may be made by creating the aircraft using known engine, airframe and wing configurations. Although performance of these first approximations will not be perfect, aircraft files can then be "tweaked" for more realistic performance. For a cognitive trainer where the performance must only be realistic, not verified as "actual", this capability allows rapid configuration of aircraft files to mimic specific aircraft without any coding.

Three open-source software projects were used to provide Object-Oriented classes abstracting arcane details of Windows threading and sockets implementations, and provide a mutex-lock for thread-safe variable access. PracticalSockets, coordinated by Baylor University's Jeff Donahoo, available from http://cs.ecs.baylor.edu/~donahoo/practical/CSockets/practical/, was used for the C++ UDP/IP implementation and available under the GNU General Public License, Version 2. A Generic C++ Thread Class by Arun N Kumar, available at http://codeproject.com/useritems/genericthreadclass.html.asp, was used for an Object-Oriented winThread implementation. No specific licensing terms were published for A Generic C++ Thread Class. The XYLock Class, by Xiangyang Liu, available from http://www.codeproject.com/useritems/XYLock.asp, was used to implement a simple spin-lock for mutually exclusive variable access between C++ threads. No specific licensing terms were published for XYLock. The code implementations for all three open-sourced projects worked as advertised and easily saved several days if not weeks over learning low-level Windows specific API's.

One open-source software project was used to access Direct-X game port I/O from within the Java application to enable reading the flight controls directly. CentralNexus, by George Rhoten and others, is available from http://sourceforge.net/projects/javajoystick/ and provides the Java application game port functionality via the packages Java Native Interfaces to C++ code. It is available under the Artistic license and no modifications were necessary to implement this package.

2. Interface Implementations and Considerations

a) Administration/Ease of Use

This was not a design consideration for this implementation.

b) Capable of Natural Flight Context

Software factors in generating a natural flight context primarily centered about minimizing latency, integration of flight controls and addition of an AFCS subsystem. A Java application was implemented as the overall system interface, taking flight control inputs directly and providing them to X-Plane; providing AFCS based trim inputs to X-Plane; passing X, Y, Z heading, pitch, roll (x, y, z, h, p, r) to the display application and serving as a data collection module.

Latency was a primary concern in the overall simulator design, both to maintain smoothness of motion, but to also avoid unacceptable delays from initial control movement to onset of motion in the visuals. Containing all network traffic inside two dedicated local switches and using short cables minimized physical network time delays. The longest delay reported via the ping tool was less than 2 ms for any link, and averaged less than 1 ms. Using the Model-View-Controller design pattern, the display subsystem was isolated from any run-time computation that was not directly related to rendering the scene and a minimum threshold of 30 fps was set for the visual display system to maintain smooth visuals. This left the display system master computer with the simple tasks of receiving the (x, y, z, h, p, r) information via UDP packets, directly updating the pilot's viewpoint (a Vega vgObserver) and promulgating those updates to the two slave computers. With the terrain database alone the system rendered at a steady 40 fps with Vega statistics displayed and various debug notification options enabled. Typically Vega applications will perform at higher fps values with these options off, but performance was not measured with them disabled. The vegetation densities used for the treatments were tested extensively to ensure that worst-case rendering conditions were still 30 fps or better.

X-Plane had all rendering options minimized to maximize frame rate, yielding a steady 60.5 fps average and approximately 58.5 fps worst case, for an approximate 2-1 Nyquist rate sampling ratio compared to the rendered scene frame rates. Visual flow was quite smooth under these conditions so no predictive positioning algorithms were necessary within the rendering module. Data packet rate measurements of X-Plane data received at the Java module also showed those same rates.

The Java application has three run-time functions: flight control inputs, stability augmentation and data collection. Data collection will be discussed in a later subsection. The flight control input interface was handled by the CentralNexus package and called from within the main event loop contained within the *hoverfly.UDPReceiver* class. Cyclic X, cyclic Y, collective and pedals were the only values sampled during each poll of the controls.

AFCS stability augmentation was largely unimplemented in the final version, but frameworks were constructed for each axis and are contained in the afcs package. A collective-to-yaw coupling method was implemented to mimic the H-60's actual mechanical mixing. This one piece of functionality took the flight model from essentially un-hoverable due to wild yaw excursions during collective inputs, to flyable in a mode that closely resembles hovering stabilization-off flight in the H-60 and other helicopters. AFCS feedback was provided to X-Plane as trim inputs, much as the H-60 AFCS system is actually designed. This simplified handling the flight controls themselves, but suffered from limitations imposed within X-Plane on the maximum magnitude of actual control surface authority. The X-Plane limitations coupled with the inability to faithfully re-create the pilot controlled trim functions imposed by the available hardware prevented completion of an AFCS system that mimics those found in a fully stabilized military helicopter. Addition of the previously mentioned cyclic-stick upgrade and more time dedicated to implementing AFCS functionality should yield an acceptably close generic stabilization system despite lack of gradient-force trim functionality.

Upon receiving UDP packets from X-Plane, they were immediately parroted to the master display computer to minimize delays. AFCS processing was done following re-transmission of the incoming packets and the results were forwarded back to X-Plane in time for the next frame's physics computations.

The flight controls were polled and transmitted to X-Plane from within the Java application at an unrestricted rate. The Java application main loop completion was more than 10x faster than X-Planes frame update rate ensuring a flight control input was less than 3 ms time late upon starting a frame update. The 60 fps frame rate adds approximately 16 ms delay and retransmission to the Java app adds another 1 ms. Latency within the Java application is limited by the Windows2000 minimum quanta of 10 ms, but should average at approximately 5 ms. Adding another 1 ms for transmission to the master and an average of 33 ms to render and display yields a total average latency of 59 ms from initial control input to potential onset of visual motion, with an estimated worst case of 74 ms. Compared to the current Navy 2F64 SH-60F Operational Flight Trainer, which has an approximate 300 ms latency from flight control movement to onset of motion and visuals, this 4-5 fold improvement is very favorable. Also actual aircraft do not react instantaneously (zero lag) to flight control inputs, and helicopters even less so due to the dynamics of the rotor system, making the measured system delays even closer to actual aircraft delays.

c) Visual

The visuals model a section of MCAS Twenty Nine Palms commonly referred to as the Delta Corridor, Figure 14 is a typical view. The terrain is a Flight (.flt) format model with a mesh comprised of approximately 24,000 triangles and covered by two textures. The mesh was created using the Delaunay method from Digital Elevation Data (DTED) Level 2 Coverage with 30 meter spacing between elevation values and is approximately 19,000 x 19,000 meters. The textures were produced from satellite imagery contained in the Multi-Resolution Seamless Image Database (MrSID) and down-sampled to approximately 5 meter resolution for the high-definition inset and 30 meter resolution over the rest of the model. The high-definition inset was used for the immediate area around the experiment's landing zone.

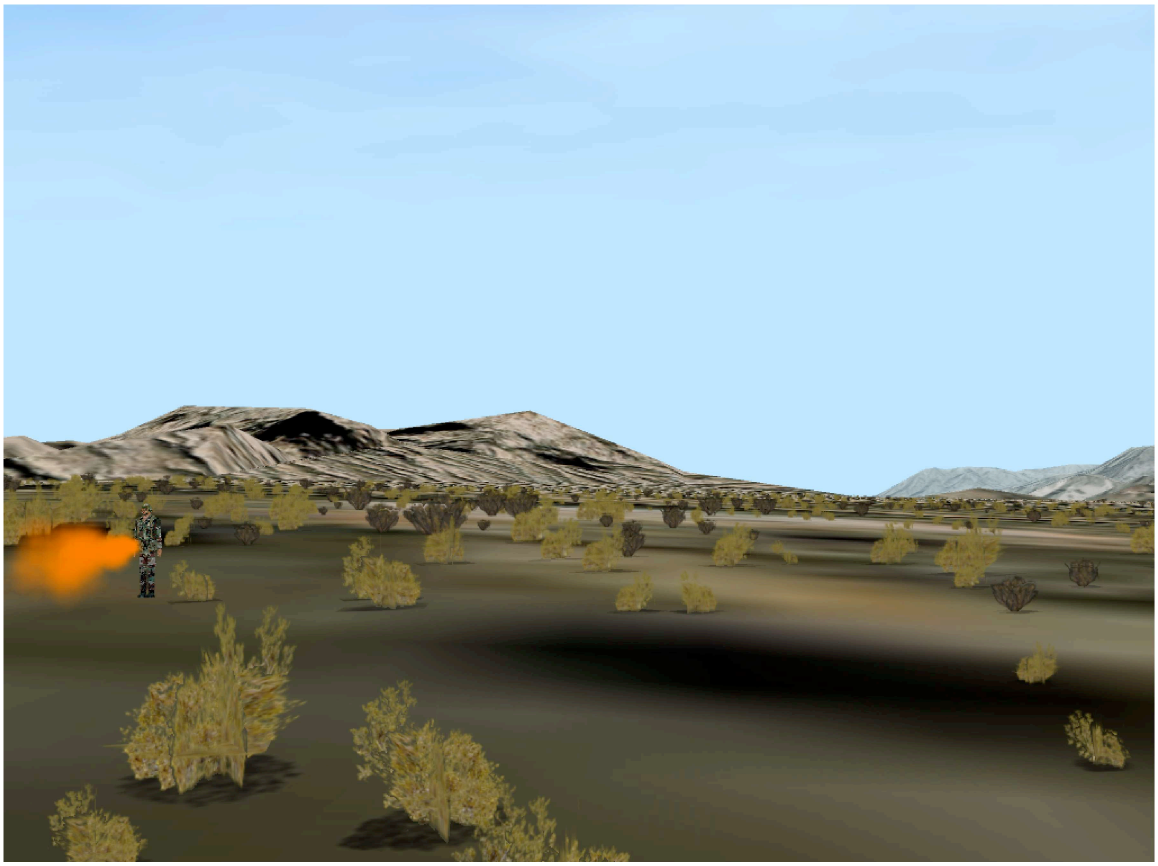

Figure 14 Delta Corridor LZ

Bushes were chosen for representation as they provide many of the critical cues necessary to properly determine self-motion and conduct a helicopter hover. Two different bushes were implemented for this experiment and are visible in Figure 14, both modeled by multiple textured polygons using alpha transparency. The green-brown bush had 6 polygons in a single LOD. The tan bush has 22 textured polygons and multiple levels of detail (LOD), with the minimum LOD (beyond 300m) representing only the shadow and largest single polygon in the model. This configuration looked good both from low angles and at altitude, minimizing frame rate hits while allowing more terrain to be covered with vegetation.

The soldier was included to inject a known size object into the visual fields and lend size context to the bushes with as much naturalness as possible. Being able to judge the relative sizes and distances using the soldier as a known reference point allowed most pilots to hover on an almost completely outside-the-cockpit scan. The soldier model (a relatively expensive 800 polygons) is the shell from a Boston-Dynamics BDI-Guy.

Bushes were distributed within the environment in a pseudo-random manner using seeds for repeatability. Circular or donut-shaped volumes can be defined for coverage with a desired density of foliage, which is also randomly rotated and then sized by a parameterized random distribution. Density values represent the probability of a bush being placed at any particular point on a one meter spaced grid within the defined region, e.g. 1.0 would have a 1% probability of placing a bush at any particular point. This also equates to how many bushes on average per 100 m^2. Bush configurations were changed at runtime between pre-set treatment densities via keyboard input. Treatment 1 was the densest with a 1.0% density, treatment 2 had a 0.25% density and Treatment 3 had no bushes. The treatment densities only apply to the 50 meter circle about the soldier, lower densities were used outside that for visual continuity and peripheral cues. All pilots except one remained within the nominal 50 meter density limits during data collection.

d) Instrumentation

The instrument panel was implemented in Vega using a generic aircraft panel with space for six flight instruments. Code and flight files were adapted from previous related NPS work by Mark Lennerton and Erik Johnson. Values were received over the network from the Java module and parsed out to methods that applied transforms resulting in appropriate rotations. Flight instruments were implemented for the following five gauges: 1) heading indicator, 2) radar altimeter, 3) airspeed indicator, 4) attitude indicator and 5) barometric altimeter.

e) Data Collection and Control

Data collection minimized its effects on latency by storing data in a Vectors for file output upon run completion with data collection runs initiated via GUI button actions for each treatment. The Data Collection Control Panel is presented as Figure 15. Helicopter position and altitude data was collected continuously and automatically at frame rate upon activation of a treatment button, except for practice runs. The subject's drift calls were prompted by system beeps at ten second intervals (also initiated with the single button press) and recorded by the experiment facilitator by pressing the appropriate clock position button.

Following completion of a subject's data runs, position data files were pre-processed with *analysis.Pre-processDrift* to generate the actual drift data files used to compare against the pilots called drift values. Manual inspection was also accomplished to ensure rapid direction changes or "kinks" in the flight plot did not adversely affect the computed drift values. Required changes to the drift files were made with the helper utility *analysis.ManualAdjust*. Ground traces were produced with *analysis.AnalyzeData*, options are available for various resolutions and defining an offset or "slewed" center point for the plot, the GUI panel is shown in Figure 16Figure 16 Data Analysis plot Creation Panel.

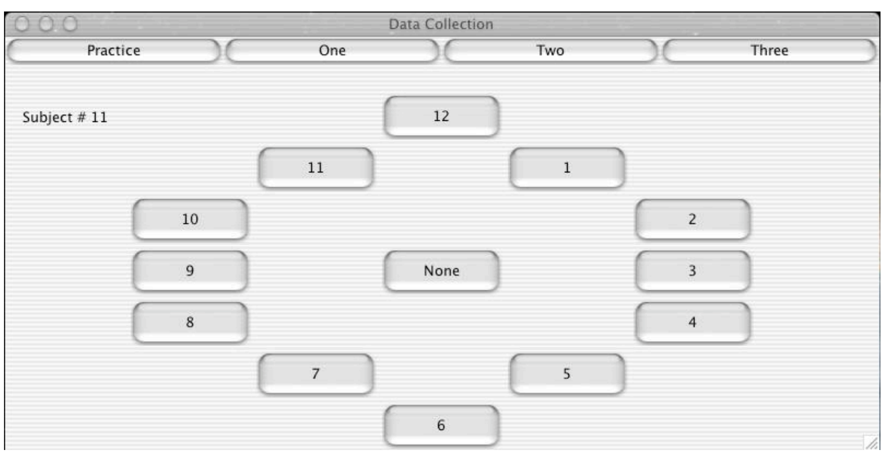

Figure 15 Data Collection Control Panel

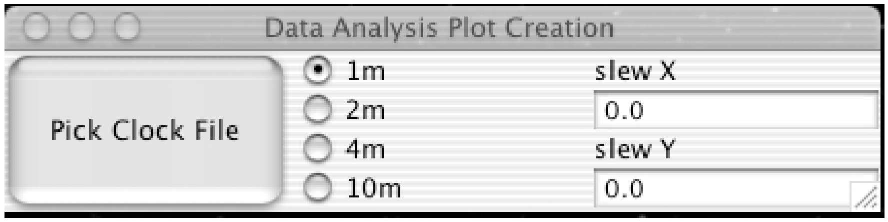

Figure 16 Data Analysis plot Creation Panel

The final numerical data was extracted with the helper applications *analysis.DriftCorrelationCounter* and *analysis.DetermineSweptVolume*. Drift correlation between called and actual drifts was simply a count of how many points matched within +/- one clock position (or 45°). The appropriate positional measure for the experiment as limited by flight model stability was to determine relative positional stability, measured by a total linear error value. It is computed by summing the linear distances between an average point and each recorded position point. Two positional average points were used, the average position for the first half of the data collection run and likewise for the second half of the run. Two average points were used to account for plot patterns that had clumps, separated by short distances (essentially created by a relatively stable hover, loss of stability and associated drift, and recovery of a stable hover in a different spot). The requirement was for the pilots to maintain as stable a hover as possible, not to maintain a hover over a particular spot, using two average points best supported measuring that relative positional stability.

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IV. METHODOLOGY

A. EXPERIMENT OVERVIEW

To determine a baseline for the visual field requirements that support the task of precisely hovering a helicopter at a generic unprepared landing site, the experiment evaluated hover performance using professional military helicopter pilots as subjects. A sparse constructive cockpit was placed within an immersive 180° widescreen display system (as shown in Figure 17) and flight dynamics handled by a commercial PC flight simulation. A desert scene from a commonly used training range was used, incorporating dynamically reconfigurable vegetation for the treatments. Helicopter positional data was continuously recorded, as well as pilot verbal assessments of aircraft drift during each data run. The treatments assessed were 1.0%, 0.25% and 0% density coverage by small tumbled-like bushes (particulars describing density are discussed in Ch. III, Section C.)

Figure 17 Virtual Cockpit set-up

B. SUBJECTS

All subjects were Naval Postgraduate School students or staff (including the Aviation Safety School) and are qualified helicopter pilots. All subjects had at least 750 hours of helicopter flight time and at least one operational tour of duty in a fleet aircraft. Prior to beginning the experiment nearly all subjects noted a significant layoff since their last flight as a pilot at the controls of a helicopter, actual times out of the cockpit ranged from 5 to 26 months. Pilots of this experience level have become automatic as described by Norman [15] in execution of their basic flying skills and techniques, desirable for this experiment as we wanted to document the efficacy of specific environmental cues in allowing experienced pilots to precisely conduct the hovering task.

C. PROTOCOLS

The experiment consisted of: pre-brief, familiarization, data collection and debrief phases. A single page summary is provided as Appendix A.

The pre-brief consisted of written mission brief explaining the flight context and setting a tactical context for the data collection runs. The entire text of the brief is contained in Appendix B. The mission brief informed the subjects they would conduct the same troop extraction mission three separate times under different seasonal conditions. The scenario specifics were tailored to create pilot subject's acceptance of the experiments data collection requirements, three minutes of hovering in as stable a position as possible. It also primed subjects that the helicopter Automatic Flight Stability Systems was damaged by enemy action. This was done because the flight model and flight controls injected artificial difficulties compared to a fully functional and stable military helicopter. Specific issues are discussed in hardware/software descriptions and future work. Reinforcing to subjects the helicopter was damaged as part of the current mission, and the mission was troop extraction with potential hostile forces inbound was done to guard against rejection of the simulation out of hand as "too squirrelly" to be realistic from a flight model standpoint and motivation to continue the mission (data collection) under conditions that would dictate a mission abort for peacetime training.

With the implementation limitations on helicopter stability, the experiment was not a test of a pilots ability to hold a steady hover, but primarily a test of the pilots ability to correctly determine drift, drift rate and make appropriate corrective flight control inputs. Because the helicopter was not completely artificially stabilized it actually made for a better test of the pilots perception of the virtual helicopters movements. Errors and corrections would have been much smaller in a fully stabilized flight model and may have washed-out VE effects with pilot driven variance and skill atrophy due to significant time out of the cockpit for all subjects. This made the test more focused on motion detection and determination/implementation of gross control response, skills that are not particularly perishable compared to the extremely fine motor control techniques used in actual mission flight that is continuously trained and honed during a flying tour.

The mission brief also introduced the subject to the data collection voice calls indicating their perception of aircraft drift. A metaphor of communication with the crew chief during the hover was described and used generic terminology all helicopter aviators are familiar with, regardless of mission specialty. The experimental consent forms are contained in Appendix C and a Simulator Sickness Questionnaire [16] was also administered prior to beginning the familiarization phase to baseline subjects. The full pre-questionnaire is contained in Appendix D.

Familiarization consisted of approximately ten minutes flight time in the simulator prior to data collection. Nearly all subjects showed marked improvement by the five to seven minute point, showing the ability to stabilize the helicopter hover position for at least short periods of time, vice constant gross over the ground motion. During the last two to three minutes of familiarization flight, subjects were given practice on the verbal prompt-communication sequence. All subjects displayed proficiency in making the drift report responses prior to data collection. No subjects required more than ten minutes familiarization time to gain enough proficiency with the simulator to be considered ready, by themselves and the author, for data collection.

The data collection consisted of the same constructive mission, troop recovery via Jacobs ladder, repeated for each of three visual scene treatments. Prior to each run the subjects landed the helicopter to allow scenario treatments to be initialized without risk of spurious inputs building and causing disconcerting aircraft behavior upon resumption of the runs. This was also done as a method to avoid simulator sickness from non-pilot caused aircraft motion. Then the environmental treatment was applied and the aircraft position reset to a common starting point. Treatments took between 10 and 20 seconds to build and display within the Vega visuals framework during which the visuals were frozen. The repositions were snap repositions that propagated at the completion of the Vega reconfiguring, again best case for avoiding simulator sickness. Once visuals un-froze, indicated by the repositioning and flowing of the orange marker smoke, the subjects pulled back into a hover and determined when the felt stable enough to begin data collection, this was not always a completely stable hover. The experiment administrator then initiated a three-minute timer via a GUI button in the experiments Java based control panel. The timer also provided system beeps at ten second intervals to prompt the subjects for drift calls that were recorded by the administrator via dedicated clock position buttons in control panel. Following completion of the three minute segment, collected data was automatically dumped to disk in two files, one containing the time stamped drift clock-position calls and the other containing time stamped helicopter position data with samples taken at 15-35 millisecond intervals.

Debrief consisted of a Simulator Sickness Questionnaire and anecdotal questions concerning simulator performance. The anecdotal information was requested primarily to help determine potential improvements for future work and do not bear directly on the results of this study.

D. EXPERIMENTAL DESIGN

A three treatment, within-subjects design was used to attempt to determine the relative utility of each treatment's environment in providing motion and positional data to the subjects. All subjects flew all three treatments, and the order each treatment was presented to a subject was pre-determined to ensure a balanced order distribution to guard against bias from learning effects.

The independent variable was the environment treatment. Each of the three treatments used a seed driven random placement/sizing/orientation algorithm to populate the scene with vegetation. Each treatment's seed was consistent for all participants, ensuring all participants received the identical visual presentations for the same treatment. Reasons for choosing randomizing algorithms vice fully pre-determined treatments are discussed in the Chapter III. All other controllable aspects of the simulation were held constant across both subjects and treatments.

The dependent variables were the subject's assessment of drift at the prompted ten-second intervals and helicopter position. The primary data, the subjects drift assessments, were compared to time-averaged actual aircraft drift with manual adjustments made to the computed drift in cases of obvious drift changes represented by kinks in the flight path data. The subject's assessment was considered the primary data as it is not confounded by the artificial level of difficulty imposed by the simulator apparatus and flight model, nor is direction determining ability a perishable skill that requires a significant amount of practice to regain (such as hovering an un-stabilized helicopter). It is also **the baseline performance limiter**, if a pilot cannot adequately determine the aircraft drift motion, there is no possibility of consistently determining the correct control inputs required to make to make corrections regardless of how faithful flight control configurations are or the stability of the flight model.

Helicopter hover position stability was analyzed by integrating the linear errors from the average position for the first half and second half of the runs. These factors are compared relatively as corroborative evidence. Actual pilot performance was expected to be inadequate to execute a real Jacobs Ladder extraction mission due to previously mentioned factors and limited practice time.

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V. EXPERIMENT RESULTS

A. GENERAL INFORMATION

The primary goal of this thesis is to determine the minimum level of visual detail that supports precision helicopter flight. Data resulting from the experimental protocol as described in Chapter IV and flown by the ten subjects is contained in Figure 18. Individual ground-track / drift comparison plots are contained in Appendix E.

Subject	Treatment	order	vol	matches
1	1	3	1462.095	18
1	2	2	2558.853	15
1	3	1	2656.775	18
2	1	2	1008.447	17
2	2	1	1508.313	17
2	3	3	1569.607	15
3	1	2	1615.764	18
3	2	3	1656.093	17
3	3	1	1882.733	15
4	1	3	1084.195	16
4	2	2	2015.616	16
4	3	1	2577.694	14
5	1	2	1019.681	17
5	2	3	1617.955	17
5	3	1	1966.623	16
6	1	1	743.429	17
6	2	3	1220.930	18
6	3	2	1721.560	13
7	1	1	471.920	18
7	2	2	728.975	17
7	3	3	1406.540	15
8	1	3	7124.010	15
8	2	1	5484.460	16
8	3	2	9366.340	12
9	1	1	509.745	18
9	2	3	683.512	18
9	3	2	745.635	15
10	1	2	937.982	18
10	2	1	1026.830	15
10	3	3	1885.550	18

Figure 18 Data Summary

Subject, *Treatmen*t and *order* are self-explanatory, the *vol* effect is the total integrated linear error, measuring relative positional stability, smaller numbers indicate a more stable hover. The *matches* are the number of matches between the pilots called drift values (by clock angle) and the actual aircraft motion +/- one clock angle.

B. SUBJECTS ASSESSMENT OF HELICOPTER DRIFT

The *matches* data is evaluated to determine the relative effects of the treatments on the pilots ability to determine drift directions. Basic summary statistics for each treatment are listed in Figure 19, and a Boxplot is provided as Figure 20.

```
Treatment:1           The most bushes (1% coverage)
    Mean: 17.200000
  Median: 17.500000
 Total N: 10.000000
Std Dev.:  1.032796
-------------------------------------------
Treatment:2           Just a few bushes (0.25% coverage)
    Mean: 16.600000
  Median: 17.000000
 Total N: 10.000000
Std Dev.:  1.074968
-------------------------------------------
Treatment:3           No bushes (0% coverage)
    Mean: 15.100000
  Median: 15.000000
 Total N: 10.000000
Std Dev.:  1.911951
```

Figure 19 Summary Statistics for *matches*

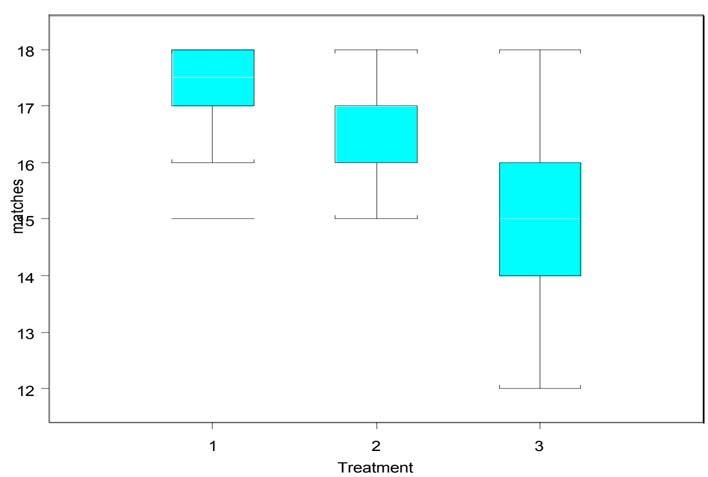

Figure 20 Number of *matches* by *Treatment*

1. The Model

An ANOVA comparison was conducted on the dependent variables *Subject* and T*reatment* for effect on *matches* with the results presented as Figure 21. The *matches* effect p-value of 0.0076 (α = .05) indicates there is a difference in the mean values for the three treatments. The *Subject* variable is not of interest directly but including it removes *Subject* effects from the residuals and makes the task of verifying the ANOVA model more precise.

```
> anova(aov(matches ~ Subject + Treatment, data = sweptVol))
Analysis of Variance Table
Response: matches
Terms added sequentially (first to last)
           Df   Sum of Sq  Mean Sq   F Value   Pr(F)
Subject    9    20.3       2.25556   1.245399  0.3293047
Treatment  2    23.4       11.70000  6.460123  0.0076783
Residuals  18   32.6       1.81111
```

Figure 21 ANOVA for *matches* by *Treatment* Effect

2. Verification of the Model

There was a very strong learning effect in flying the simulator that was compensated for by balanced randomization of each subject's treatment order. To verify the randomization successfully washed out the learning effect an ANOVA comparison was conducted on the dependent variable *order* for it's effect on *matches* with the results presented as Figure 22. The *order* effect p-value of 0.46 (α = .05) indicates there is no significant difference in the mean values due to order of presentation.

```
> anova(aov(matches ~ order, data = sweptVol))
Analysis of Variance Table
Response: matches
Terms added sequentially (first to last)
           Df   Sum of Sq  Mean Sq   F Value   Pr(F)
Order      2    4.2        2.10000   0.7864078 0.4656341
Residuals  27   72.1       2.67037
```

Figure 22 ANOVA for *matches* by Treatment *order*

The last step in verifying the validity of the ANOVA's underlying assumptions is an examination of the residuals. If the residuals display a normal distribution, then the assumption of normalcy for the underlying data is reasonable as is the model used in the ANOVA comparison. The first test for normalcy is a quantile-quantile comparison plot as shown in Figure 23. The central quantile-quantile plot derives from the (30) residuals and the surrounding eight plots are random normal distributions (30 points). The central plot is no less linear than either of the plots in the lower corners, showing plausibility that the residuals are normally distributed.

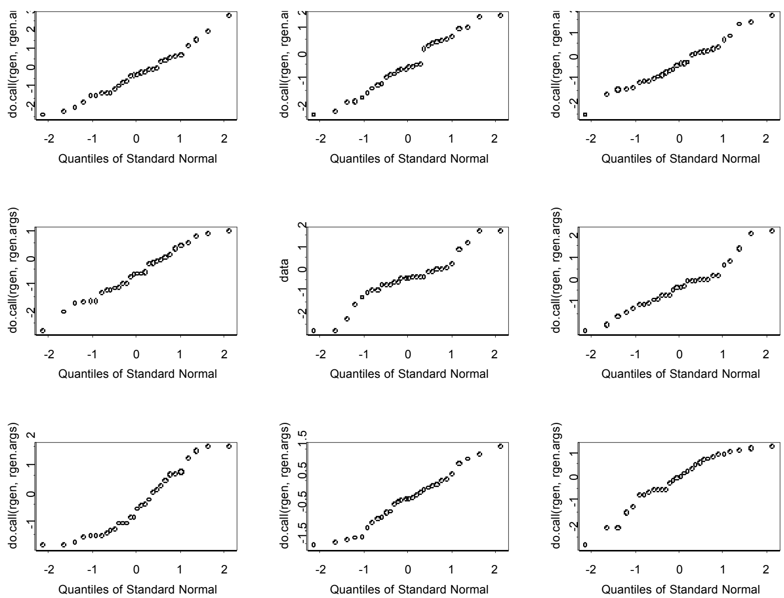

Figure 23 Residuals Quantile-Quantile Plot (*matches*)

The V4 residuals plot of Figure 24 provide further visual tests for the residuals normalcy. The plots all appear to be reasonable normal distributions (the lower right plot is the same qq-plot as in the center of Figure 23).

The final plot, Figure 25 is the fitted-residuals plotted against the overall order the data points they were collected (index). The ends both exhibit very similar ranges and with the relatively small number of points there is no compelling, consistent evidence of heteroscedasticity. Thus it can be assumed with relative safety that the residuals are normally distributed and the ANOVA comparison model is valid.

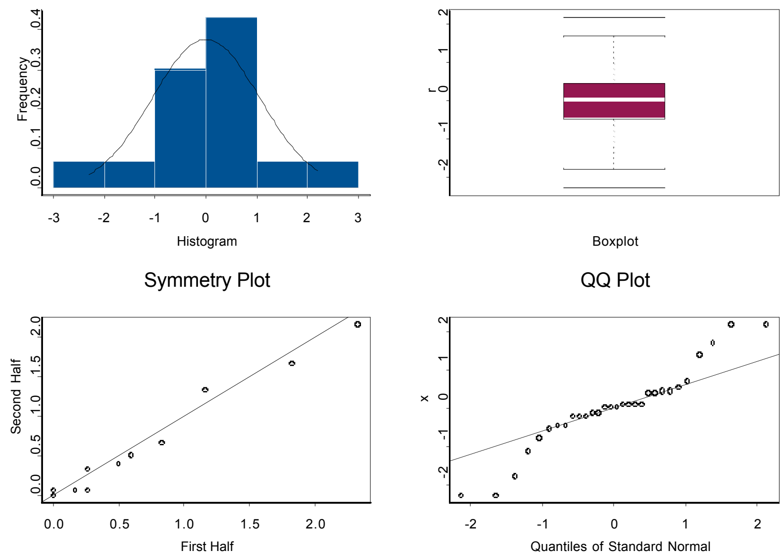

Figure 24 V4 residuals Plot (*matches*)

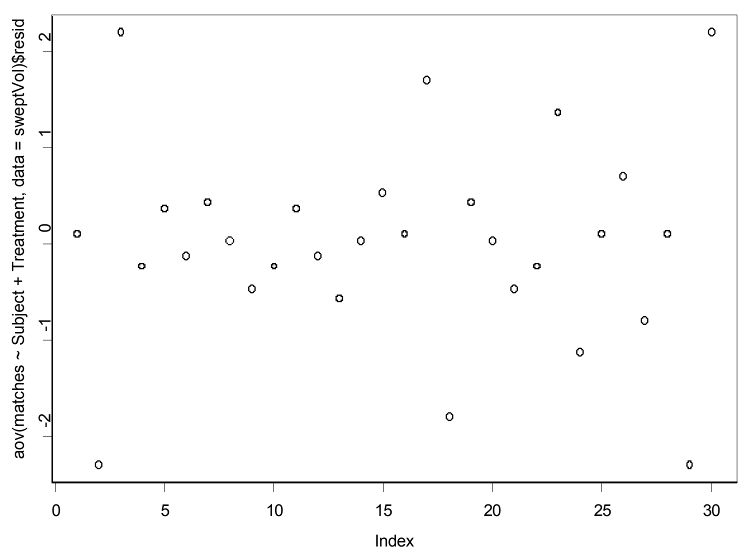

Figure 25 Fitted Residuals (*matches*)

3. Power Analysis

A power analysis was conducted on the verified model to find the significance in guarding against type II errors and accepting a positive result where it did not actually exist. With an □□value of .05, the power of these results are .864 for a difference between treatments one and three, making it very unlikely that we falsely detected a significant difference between them. The power of these results are .248 for a difference between treatments one and two, making it possible that we falsely detected a significant difference between them. More data-points would be required to lower the possibility of a type II error.

C. HOVER POSITION STABILITY

The *vol* data is evaluated to determine the relative effects of the treatments on the pilots ability to maintain a stable aircraft position. While this is not considered a primary measure of success in holding a hover, the relative performance between treatments in the pilot's ability to determine drift and control corrections is highly useful in determining and confirming the effects of treatment visuals. Given a better hover stability augmentation subsystem it is reasonable to assume this absolute measure of hover performance should improve as well. Basic summary statistics for each treatment are listed in Figure 26, and a Boxplot is provided as Figure 27.

```
Treatment:1          The most bushes (1% coverage)
    Mean: 1597.7267
  Median: 1014.0638
 Total N:   10.0000
Std Dev.: 1975.4005
--------------------------------------------
Treatment:2          Just a few bushes (0.25% coverage)
     Min:  683.512
    Mean: 1850.154
  Median: 1563.134
 Total N:   10.000
Std Dev.: 1399.926
--------------------------------------------
Treatment:3          No bushes (0% coverage)
    Mean: 2577.906
  Median: 1884.142
 Total N:   10.000
Std Dev.: 2447.326
-------------------------------------------
```

Figure 26 Summary Statistics for *vol*

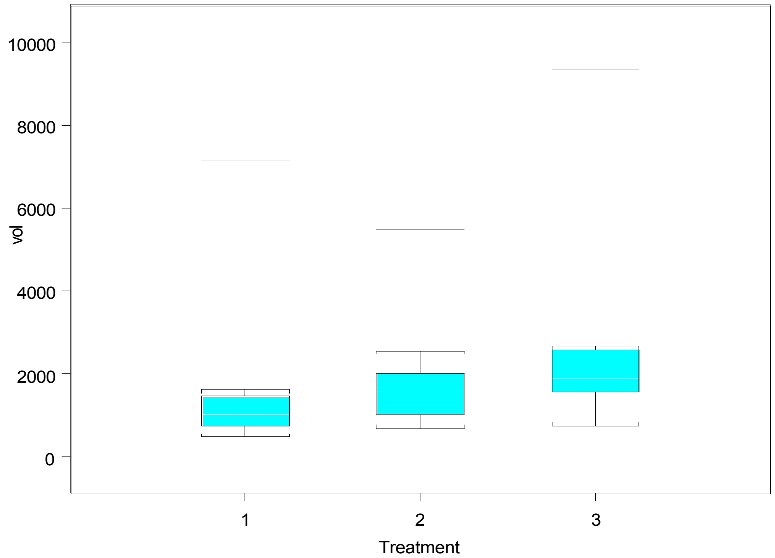

Figure 27 Values of *vol* by *Treatment*

1. The Model

The variance of each treatment is not consistent and the outlying data from subject 8 catastrophically mask the treatment effects making an ANOVA comparison of the data untenable. A logarithmic transform was applied in an attempt to resolve these problems and allow use of the ANOVA transform. The results of the transformation were encouraging so the an ANOVA comparison was conducted on the dependent variables *Subject* and T*reatment* for effect on *vol* with the results presented as Figure 28. The *matches* effect p-value of less than 0.0001 (α = .05) indicates there is a definite difference in the mean values for the three treatments. The *Subject* variable is not of interest directly but including it removes *Subject* effects from the residuals and makes the task of verifying the ANOVA model more precise.

```
> anova(aov(log(vol) ~ Subject + Treatment, data = sweptVol))
Analysis of Variance Table

Response: log(vol)

Terms added sequentially (first to last)
           Df   Sum of Sq  Mean Sq   F Value   Pr(F)
Subject     9   11.66001   1.295556  35.64029  1.153000e-009
Treatment   2   1.80068    0.900339  24.76800  6.786323e-006
Residuals  18   0.65432    0.036351
```

Figure 28 ANOVA for *vol* by *Treatment* Effect

2. Verification of the Model

Again, to verify the randomization successfully washed out the learning effect an ANOVA comparison was conducted on the dependent variable *order* for it's effect on *vol* with the results presented as Figure 29. The *order* effect p-value of 0.95 (α = .05) indicates there is no significant difference in the mean values due to order of presentation.

```
> anova(aov(log(vol) ~ order, data = sweptVol))
Analysis of Variance Table
Response: log(vol)
Terms added sequentially (first to last)
           Df   Sum of Sq  Mean Sq    F Value   Pr(F)
Order      2    0.05108    0.0255415  0.049034  0.9522327
Residuals  27   14.06392   0.5208859
```

Figure 29 ANOVA for *vol* by Treatment *order*

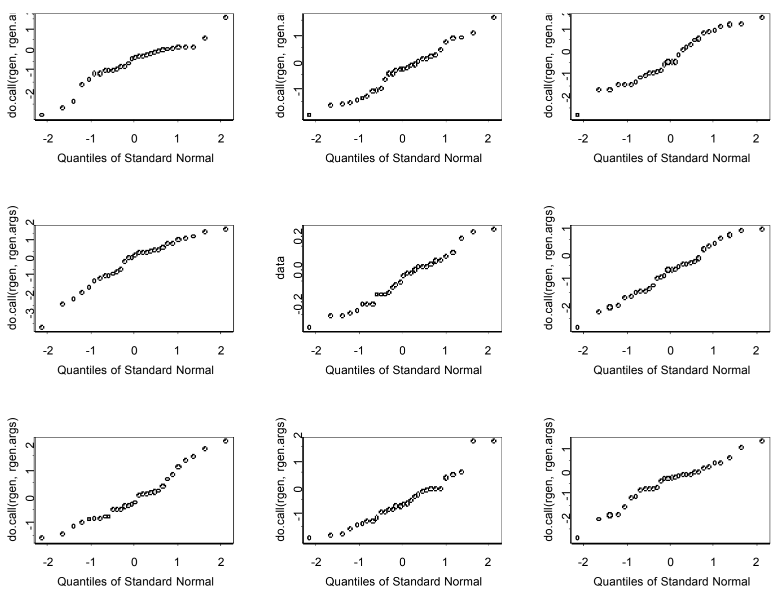

Figure 30 Residuals Quantile-Quantile Plot (*vol*)

The last step in verifying the validity of the ANOVA's underlying assumptions is an examination of the residuals. If the residuals display a normal distribution, then the assumption of normalcy for the underlying data is reasonable as is the model used in the ANOVA comparison. The first test for normalcy is a quantile-quantile comparison plot as shown in Figure 30. The central quantile-quantile plot derives from the (30) residuals and the surrounding eight plots are random normal distributions (30 points). The central plot is no less linear than either of the plots in the lower corners, showing plausibility that the residuals are normally distributed.

The V4 residuals plot of Figure 31 provide further visual tests for the residuals normalcy. The plots all appear to be reasonable normal distributions (the lower right plot is the same qq-plot as in the center of Figure 30).

The final plot, Figure 32 is the fitted-residuals plotted against the overall order the data points were collected (index). The plot exhibits a consistent spread throughout the data and therefore no evidence of heteroscedasticity. Thus it can be assumed with relative safety that the residuals are normally distributed and the ANOVA comparison model is valid.

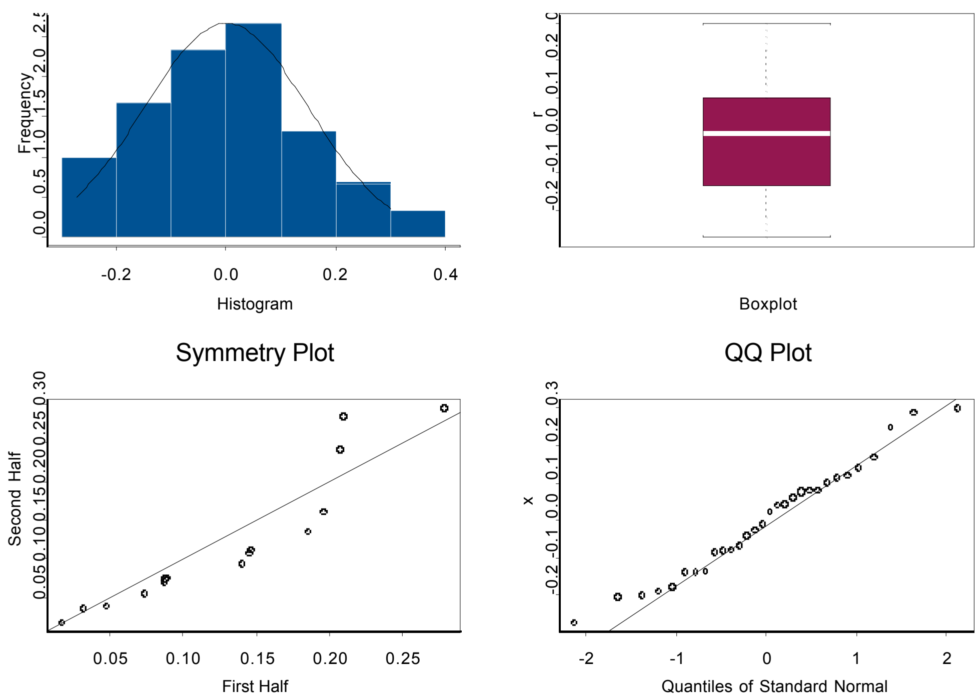

Figure 31 V4 residuals Plot (*vol*)

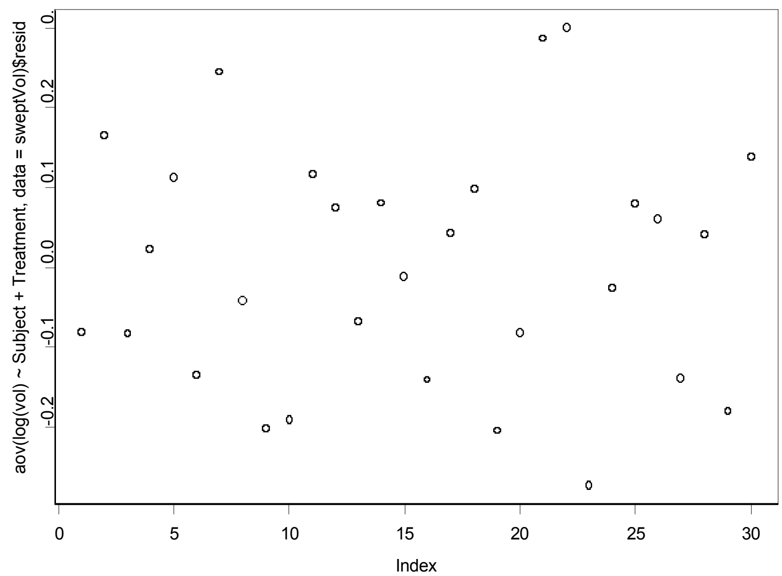

Figure 32 Fitted Residuals (*vol*)

3. Power Analysis

A power analysis was conducted on the verified model to find the significance in guarding against type II errors and accepting a positive result where it did not actually exist. With an α value of .05, the power of these results are .88 for a difference between treatments one and three, making it very unlikely that we falsely detected a significant difference between them. The power of these results are .45 for a difference between treatments one and two, and .38 between treatments two and three, making it possible, that we falsely detected a significant difference between them. More data-points would be required to lower the possibility of a type II error.

D. SIMULATOR SICKNESS QUESTIONNAIRES

The simulator sickness questionnaires were inconclusive overall, primarily due to the exposure lengths of less than 20 minutes flying time. Questionnaire results are summarized in Appendix F, including the pre-flight, post-flight and effect results. The effect results are the difference between the before and after questionnaires for each subject and isolates symptoms generated by the simulation exposure itself.

Of the 9 subjects responding, only one indicated multiple instances of mild symptoms, and one indicated a single mild symptom. Most subjects noted sweating during the runs, which is a potential symptom but was primarily caused by hot equipment in an enclosed inadequately ventilated space, therefore sweating was ignored if it was the only symptom reported.

Despite the short exposure time, these results are encouraging as many current simulations generate negative effects quite readily under hover conditions. The results also do not readily conform to the premise that a wide screen peripheral display significantly enhances the onset of simulator sickness in and of itself [16]. Further testing is required to make ant lasting conclusions.

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VI. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

This thesis experiment explored the visual field requirements for supporting precision NOE helicopter flight. Based on a task analysis of hovering over an unprepared landing site, critical cues were provided via three-dimensional bushes placed within the scene and displayed in a full peripheral visual field. Ten professional military helicopter pilots flew the experiment and were evaluated on their perception of helicopter drift and the positional stability of their hovers. Upon analyzing the results of the experiment as previously described in Chapter V the following conclusions are drawn.

Three-dimensional objects are required components of a visual scene. The ANOVA results for both the positional stability and perceived drift show strong significance for a difference between the 1% density coverage of treatment 1 and the textures only of treatment 3. The additional factor of significant power displayed against making a type II error makes the result quite convincing. Therefore it appears textures alone are significantly less suited to presenting pilots the required information for precision flight. While it is possible some improvement could be gained in a texture only treatment by hyper-texturing the terrain in comparison to the 2-3 meter resolution presented in this study, the critical cue of occlusion is completely absent, also while the altitude control of the pilots was not assessed, the workload to maintain a consistent hover is higher when visual cues are inadequate (as is the case in texture only terrain) and higher workload for altitude control would likely siphon off resources that could be used for better horizontal positioning.

The required visual density lies in the vicinity of 1% The significant results noted above may be extended with an examination of other relationships within the data set. The relatively weak statistical power between treatments 1 & 2 and 2 & 3 show the required density is definitely above the .25% level of treatment 2, and needs to be nearer the 1% of treatment 1 to show these levels of significance. Further data collection is required to exactly determine the relevant thresholds, but it is unlikely that there will be a large computational bonus by lowering the threshold small amounts below 1%.

Although the differences in the *matches* data between treatment 1 & 2 were quite small, potentially leading to the conclusion that the required object density could be significantly lower than 1%, even treatment 1 had a less than perfect mean (17.0 out of 18) and median (17.5 out of 18) indicating the threshold for perfect drift determination may actually be somewhat higher than 1% object density. Providing some allowances for high pilot workload during the data collection runs accounts for a portion of the misperceived drift directions and would move the resulting mean and median even closer to a perfect 18. With the same allowances, treatment 2 should still be close enough to statistically be an insignificant difference, but the practical result is treatment 1 appears better and does not placing undue computational loads on the graphics pipeline in comparison to treatment 2.

B. FUTURE WORK

1. Improved Flight Model

Addition of appropriate AFCS functionality should be undertaken in future implementations with the expectation of much improved positional precision in hovering tasks and other low altitude maneuvers. Once the added precision meets pilot expectations, the trainer should be ready for a training transfer assessment.

It is highly recommended that future work use the Flight Link, Inc. G-Stick II Plus helicopter cyclic (or equivalent), which includes a four-way hat switch. Trim is an important tool for the pilot to affect both the desired flight condition (via beeper-trim) and reset control loadings on the cyclic (force-gradient trim). Although force-gradient trim is not a function of the G-Stick II Plus helicopter cyclic, this can be somewhat compensated for with the pilot's use of beeper-trim. The addition of trim capability is a pre-requisite for an effective AFCS implementation.

2. Environment Related

Similar tests should be conducted with other visual conditions as the variables. It would be useful to quantify pilot's relative hovering performance across full widescreen visuals, restricted forward-view visuals and head-tracked HMD visuals. While HMDs do not supply a full peripheral view, with head tracking they do allow a visual scan that can be used to somewhat overcome the peripheral view limitations. Coupled with longer exposure times, these tests could also examine relationships to simulator sickness.

The implementation used for dynamically changing the vegetation does not have particularly pleasing performance characteristics. A better implementation that fully shares applicable object attributes will allow far more vegetation to be displayed in any particular scene without an unacceptable frame rate hit. With this performance enhancement the implementation can also be extended to dynamically add and delete vegetation throughout the terrain in response to the helicopter's flight path. This capability is key to ensuring adequate detail is available everywhere throughout a very large terrain model without undue manual efforts.

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LIST OF REFERENCES

[1] Klein, G. (1997). The Recognition-Primed Decision Model: Looking Back, Looking Forward. In Naturalistic Decision Making, (pp. 285-292). Mahwah, NJ; Lawrence Erlbaum

[2] Card, Moran & Newell. (1983). The GOMS Model of Manuscript Editing, In Card, Moran & Newell, The Psychology of Human Computer Interaction, Hillsdale, (pp. 139-147) NJ; Lawrence Erlbaum

[3] Lowther, K., & Ware, C. (1996). Vection With Large Screen 3D Imagery. CHI 96 Electronic Proceedings, (Eds.) Ralf Bilger, Steve Guest, and Michael J. Tauber available at http://www.acm.org/sigchi/chi96/proceedings/shortpap/Lowther/lk_txt.htm. Association for Computing Machinery, New York, NY

[4] Chen, M., Fortes, P., Klatzky, R., & Long, W. (2002). Design for Peripheral Vision: Conveying Information Without Requiring Users' Focus of Attention. Available at http://www.fortes.com/projects/periphery/peripherychi2002.pdf

[5] Money, K. (1983). Theory Underlying the Peripheral Vision Horizon Device. In NASA Peripheral Vision Display Conference, Dryden Research Facility, Edwards Air Force Base.

[6] Hedges, T. (2002). Immersed in the Widescreen Cinema, Available at http://www.zerohour.net/~reed/wri/widescreen.html

[7] von der Heyde, M., Riecke, B., Cunningham, D., & Bülthoff, H. (2001). Visual-vestibular sensor integration follows a max-rule: results from psychophysical experiments in virtual reality. TWK 2001. Beiträge zur 4. Tübinger Wahrnehmungskonferenz, 142. (Eds.) Bülthoff, Gegenfurtner, Mallot, Ulrich, Knirsch-Verlag. Kirchentellinsfurt, Germany

[8] von der Heyde, M., & Bülthoff, H. (2001). Two strategies to integrate visual-vestibular self motion: comparison of landmark and optic-flow information. Perception ECVP01 Supplement, Pion

[9] Pausch, R., Crea, T., & Conway, M. (1992). A Literature Survey for Virtual Environments: Military Flight Simulators Visual Systems and Simulator Sickness. Presence: Teleoperators and Virtual Environments, 1(3), 344-363

[10] Arthur, K. (2000). Effects of Field of View on Performance with Head Mounted Displays, PhD Dissertation, University of North Carolina, Chapel Hill.

[11] Webb, N., & Griffin, M. (2002). Optokinetic Stimuli: Motion Sickness, Visual Acuity, and Eye Movements. Aviation, Space and Environmental Medicine. 73(4), 315-318.

[12] Longridge, T., Bürki-Cohen, J., Go, T., & Kendra, A. (2001) Simulator Fidelity Considerations for Training and Evaluation of Today's Airline Pilots. Proceedings of the 11th International Symposium on Aviation Psychology, Columbus, OH, Ohio State University Press.

[13] Schroeder, J. (1999). Helicopter Flight Simulation Motion Platform Requirements, NASA/TP-1999-208766, July 1999

[14] National Research Council. (1984). Theories of Motion Sickness and Adaptation, Research Issues in Simulator Sickness: Proceedings of a Workshop, 22-42, Washington DC; National Academy Press.

[15] Norman, D. (1976). Attention, Effort and Resources. In Memory and Attention: An Introduction to Human Information processing, 2nd Ed, (pp. 65). New York; Wiley and Sons

[16] Kennedy, R., Lane, N., Berbaum, K., & Lilienthal, M. (1993). Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. International Journal of Aviation Psychology, 3(3), 203-220.

APPENDIX A EXPERIMENT OUTLINE

Pre Questionnaire

Hours Training _______
Operational _______

Visual Acuity__________
Visual problems?____
____

Sim Sickness questionnaire [16]

~10 minutes of free flight controllability familiarization.

Data Collection

Six three minute trials across three treatments. Each trial will have the same task, to maintain a stable 5-foot hover to facilitate troop on load via Jacobs ladder. Treatments will vary by the density of three-dimensional vegetation within the scene. Raw data collected will be: x, y, z, h, p, r, time; with the first point being the start position. The final measure will be deviation integrated over time from the start-over point. Between each trial the subject will be given ~2 minutes to relax concentration/land as a measure to counter fatigue and simulator sickness.

Post Questionnaire

Were you satisfied with you ability to position the helicopter?

Densest Vegetation	Y / N
Sparsest Vegetation	Y / N
Mid-density Vegetation	Y / N

Describe any simulator features you found particularly helpful or disconcerting._____
____
____
____
____

Sim Sickness questionnaire [16]

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<u>APPENDIX B</u> MISSION BRIEF / PRE-MISSION FAM

MISSION BRIEF

You will execute the LZ phase of three simulated exfil missions to pick up a spec-ops element in semi-hostile territory.

The LZ is extremely soft/semi-muddy terrain preventing a landing and will be marked with an orange day flare. Optimal pick-up position will have the flare-man (a local partisan) at the 10-11 o'clock position outside the rotor arc at 20-30 yards, hovering into a slight wind from the North.

On ingress your aircraft (MH-60G, in-flight refuel probe removed) came under small arms fire and sustained some minor damage that included knocking out the AFCS and hoist systems. Because of the soft terrain, crew recovery must be by Jacobs Ladder, there is not enough time to rig alternate extraction rigs.

The LZ is currently cold, with potential hostiles inbound from the north by SUV--ETA approximately 5 minutes. Your wing was hit and aborted, the team is positively ID/localized and there is company inbound, you have been dispatched from third base to home plate single-ship…

You must hold as steady a 10-foot hover as possible during the approximately three minutes it should take to effect team recovery. To simulate ICS calls within the aircraft between yourself and the crew-chief, report your current direction of drift by the clock method (nose = 12, tail == 6) each time you hear a single beep tone, if you feel you are in a positionally steady hover, "none" or "steady" are appropriate replies.

The simulated exfils will take place at the same LZ but in different "”seasons", requiring a short transition period between missions. After the crew-chief reports all men on board, just set the aircraft down and wait for the mission commander to call for take-off.

PRE-MISSION FAM:

You will have 10 minutes for controllability familiarization under late-spring/early summer vegetation conditions. Remember this is a hurt-bird with no operational stabilization systems, so it is very susceptible to over-control.

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APPENDIX C CONSENT FORMS

PARTICIPANT CONSENT FORM

1. **Introduction.** You are invited to participate in a study of helicopter flight simulation. With information gathered from you and other participants, we hope to discover insight on visual aids used to conduct NOE maneuvers and hovering in virtual terrain. We ask you to read and sign this form indicating that you agree to be in the study. Please ask any questions you may have before signing.

2. **Background Information.** The Naval Postgraduate School NPSNET Research Group is conducting this study.

3. **Procedures.** If you agree to participate in this study, the researcher will explain the tasks in detail. There will be three sessions: 1) 15 minute pretest phase, 2) a simulator phases lasting approximately thirty five minutes in duration, during which you will be expected to accomplish a number of tasks related to NOE flight and 3) a 15 minute post-test questionnaire phase

4. **Risks and Benefits.** This research involves no risks or discomforts greater then those encountered in an ordinary simulator sortie, including slight potential for simulator sickness. The benefits to the participants are contributing to current research in helicopter flight simulation.

5. **Compensation.** No tangible reward will be given. A copy of the results will be available to you at the conclusion of the experiment.

6. **Confidentiality.** The records of this study will be kept confidential. No information will be publicly accessible which could identify you as a participant.

7. **Voluntary Nature of the Study.** If you agree to participate, you are free to withdraw from the study at any time without prejudice. You will be provided a copy of this form for your records.

8. **Points of Contact.** If you have any further questions or comments after the completion of the study, you may contact the research supervisor, Dr. Rudolph P. Darken (831) 656-7588 darken@nps.navy.mil.

9. **Statement of Consent.** I have read the above information. I have asked all questions and have had my questions answered. I agree to participate in this study.

-- --------------------------

Participant's Signature Date

-- --------------------------

Researcher's Signature Date

MINIMAL RISK CONSENT STATEMENT

NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA 93943
MINIMAL RISK CONSENT STATEMENT

Participant: VOLUNTARY CONSENT TO BE A RESEARCH PARTICIPANT IN: Evaluation of visual field requirements for precision NOE helicopter flight.

1. I have read, understand and been provided "Participant Consent Form" that provides the details of the below acknowledgments.

2. I understand that this project involves research. An explanation of the purposes of the research, a description of procedures to be used, identification of experimental procedures, and the extended duration of my participation have been provided to me.

3. I understand that this project does not involve more than minimal risk. I have been informed of any reasonably foreseeable risks or discomforts to me.

4. I have been informed of any benefits to me or to others that may reasonably be expected from the research.

5. I have signed a statement describing the extent to which confidentiality of records identifying me will be maintained.

6. I have been informed of any compensation and/or medical treatments available if injury occurs and is so, what they consist of, or where further information may be obtained.

7. I understand that my participation in this project is voluntary, refusal to participate will involve no penalty or loss of benefits to which I am otherwise entitled. I also understand that I may discontinue participation at any time without penalty or loss of benefits to which I am otherwise entitled.

8. I understand that the individual to contact should I need answers to pertinent questions about the research is Professor Rudy Darken, Principal Investigator, and about my rights as a research participant or concerning a research related injury is the Modeling Virtual Environments and Simulation Chairman. A full and responsive discussion of the elements of this project and my consent has taken place.

Medical Monitor: Flight Surgeon, Naval Postgraduate School

____

Signature of Principal Investigator Date

____

Signature of Volunteer Date

____

Signature of Witness Date

PRIVACY ACT STATEMENT

NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA 93943
PRIVACY ACT STATEMENT

1. Authority: Naval Instruction

2. Purpose: Hover performance data will be collected to enhance knowledge, and to develop tests, procedures, and equipment to improve the development of Virtual Environments.

3. Use: Hover performance data will be used for statistical analysis by the Departments of the Navy and Defense, and other U.S. Government agencies, provided this use is compatible with the purpose for which the information was collected. Use of the information may be granted to legitimate non-government agencies or individuals by the Naval Postgraduate School in accordance with the provisions of the Freedom of Information Act.

4. Disclosure/Confidentiality:

   a. I have been assured that my privacy will be safeguarded. I will be assigned a control or code number which thereafter will be the only identifying entry on any of the research records. The Principal Investigator will maintain the cross-reference between name and control number. It will be decoded only when beneficial to me or if some circumstances, which is not apparent at this time, would make it clear that decoding would enhance the value of the research data. In all cases, the provisions of the Privacy Act Statement will be honored.

   b. I understand that a record of the information contained in this Consent Statement or derived from the experiment described herein will be retained permanently at the Naval Postgraduate School or by higher authority. I voluntarily agree to its disclosure to agencies or individuals indicated in paragraph 3 and I have been informed that failure to agree to such disclosure may negate the purpose for which the experiment was conducted.

   c. I also understand that disclosure of the requested information, including my Social Security Number, is voluntary.

____

Signature of Volunteer   Name, Grade/Rank (if applicable)   DOB   SSN   Date

____

Signature of Witness   Date

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APPENDIX D QUESTIONNAIRES

PRE-QUESTIONNAIRE

Hours: Total ______
Operational _______; Model Aircraft ________________

Time since last flight as pilot: __________________

Visual Acuity ___________
Visual problems? ____
____

For the following conditions, circle the choice that most closely indicates how you feel right now:

General Discomfort	*None*	*Slight*	*Moderate*	*Severe*
Fatigue	*None*	*Slight*	*Moderate*	*Severe*
Headache	*None*	*Slight*	*Moderate*	*Severe*
Eye Strain	*None*	*Slight*	*Moderate*	*Severe*
Difficulty Focusing	*None*	*Slight*	*Moderate*	*Severe*
Increased Salivation	*None*	*Slight*	*Moderate*	*Severe*
Sweating	*None*	*Slight*	*Moderate*	*Severe*
Nausea	*None*	*Slight*	*Moderate*	*Severe*
Difficulty Concentrating	*None*	*Slight*	*Moderate*	*Severe*
Fullness of Head	*None*	*Slight*	*Moderate*	*Severe*
Blurred Vision	*None*	*Slight*	*Moderate*	*Severe*
Dizzy(Eyes Open)	*None*	*Slight*	*Moderate*	*Severe*
Dizzy(Eyes Closed)	*None*	*Slight*	*Moderate*	*Severe*
Vertigo	*None*	*Slight*	*Moderate*	*Severe*
Stomach Awareness	*None*	*Slight*	*Moderate*	*Severe*
Burping	*None*	*Slight*	*Moderate*	*Severe*

POST-QUESTIONNAIRE

For the following conditions, circle the choice that most closely indicates how you feel right now:

General Discomfort	*None*	*Slight*	*Moderate*	*Severe*
Fatigue	*None*	*Slight*	*Moderate*	*Severe*
Headache	*None*	*Slight*	*Moderate*	*Severe*
Eye Strain	*None*	*Slight*	*Moderate*	*Severe*
Difficulty Focusing	*None*	*Slight*	*Moderate*	*Severe*
Increased Salivation	*None*	*Slight*	*Moderate*	*Severe*
Sweating	*None*	*Slight*	*Moderate*	*Severe*
Nausea	*None*	*Slight*	*Moderate*	*Severe*
Difficulty Concentrating	*None*	*Slight*	*Moderate*	*Severe*
Fullness of Head	*None*	*Slight*	*Moderate*	*Severe*
Blurred Vision	*None*	*Slight*	*Moderate*	*Severe*
Dizzy(Eyes Open)	*None*	*Slight*	*Moderate*	*Severe*
Dizzy(Eyes Closed)	*None*	*Slight*	*Moderate*	*Severe*
Vertigo	*None*	*Slight*	*Moderate*	*Severe*
Stomach Awareness	*None*	*Slight*	*Moderate*	*Severe*
Burping	*None*	*Slight*	*Moderate*	*Severe*

Were you satisfied with your ability to position the helicopter?

Densest Vegetation	*Yes*	*No*
Sparsest Vegetation	*Yes*	*No*
Mid-density Vegetation	*Yes*	*No*

Please note any simulator features you found particularly helpful or disconcerting:__

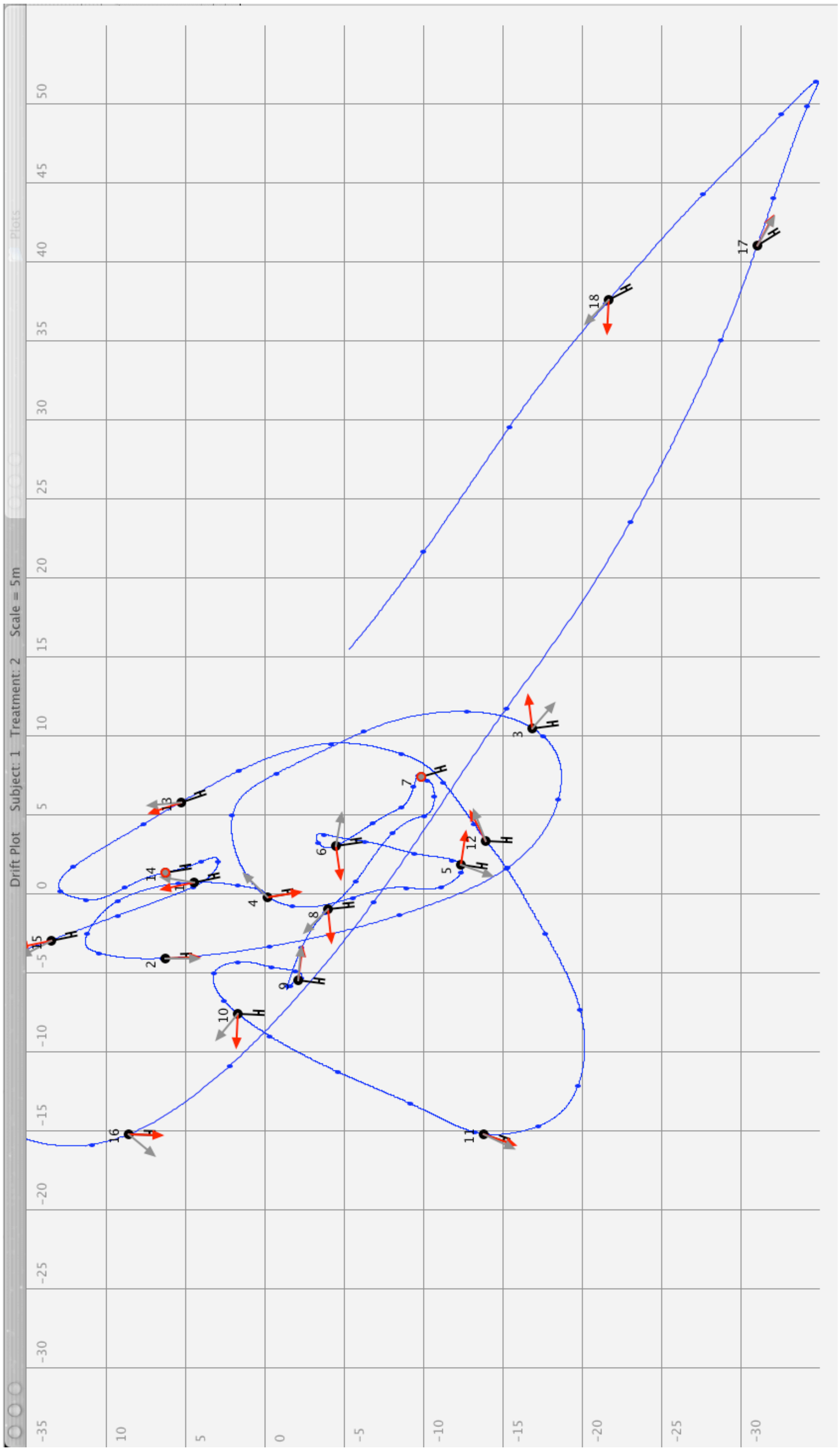
____

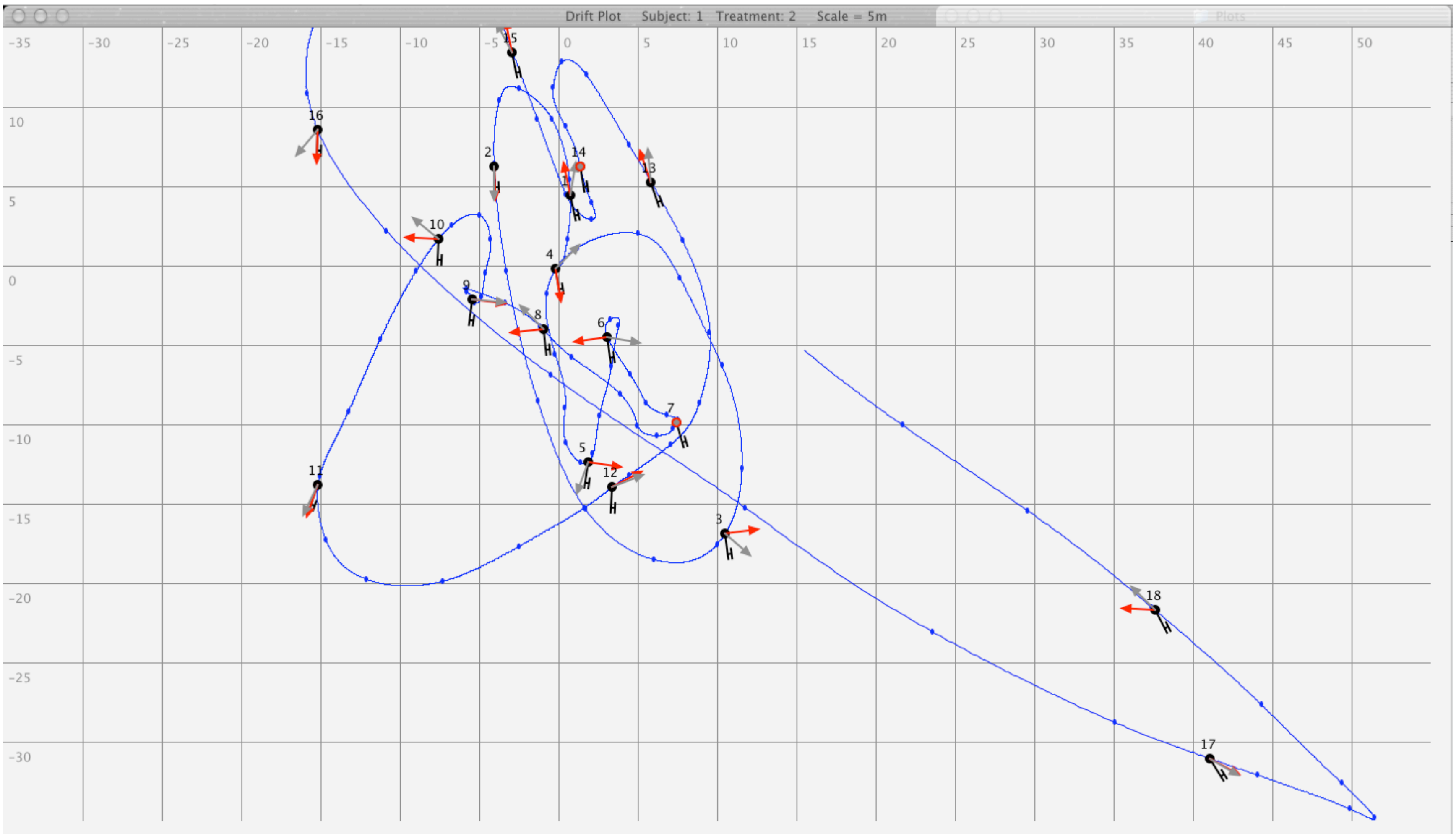
____

____

<u>APPENDIX E</u>   DATA PLOTS

Subject 1




Drift Plot Subject: 1 Treatment: 2 Scale = 5m
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
10
5
0
-5
-10
-15
-20
-25
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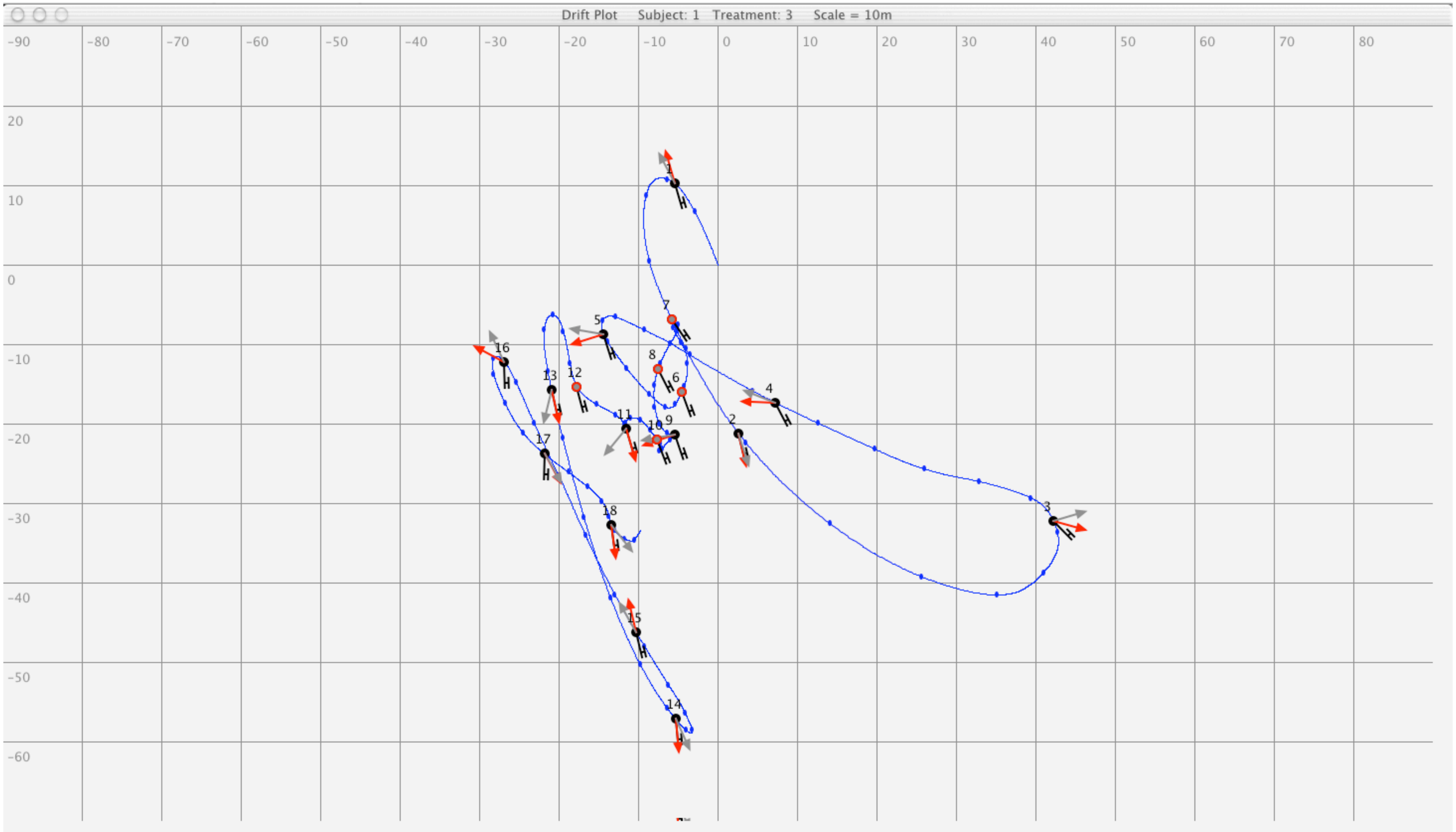
Drift Plot Subject: 1 Treatment: 3 Scale = 10m
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
20
10
0
-10
-20
-30
-40
-50
-60
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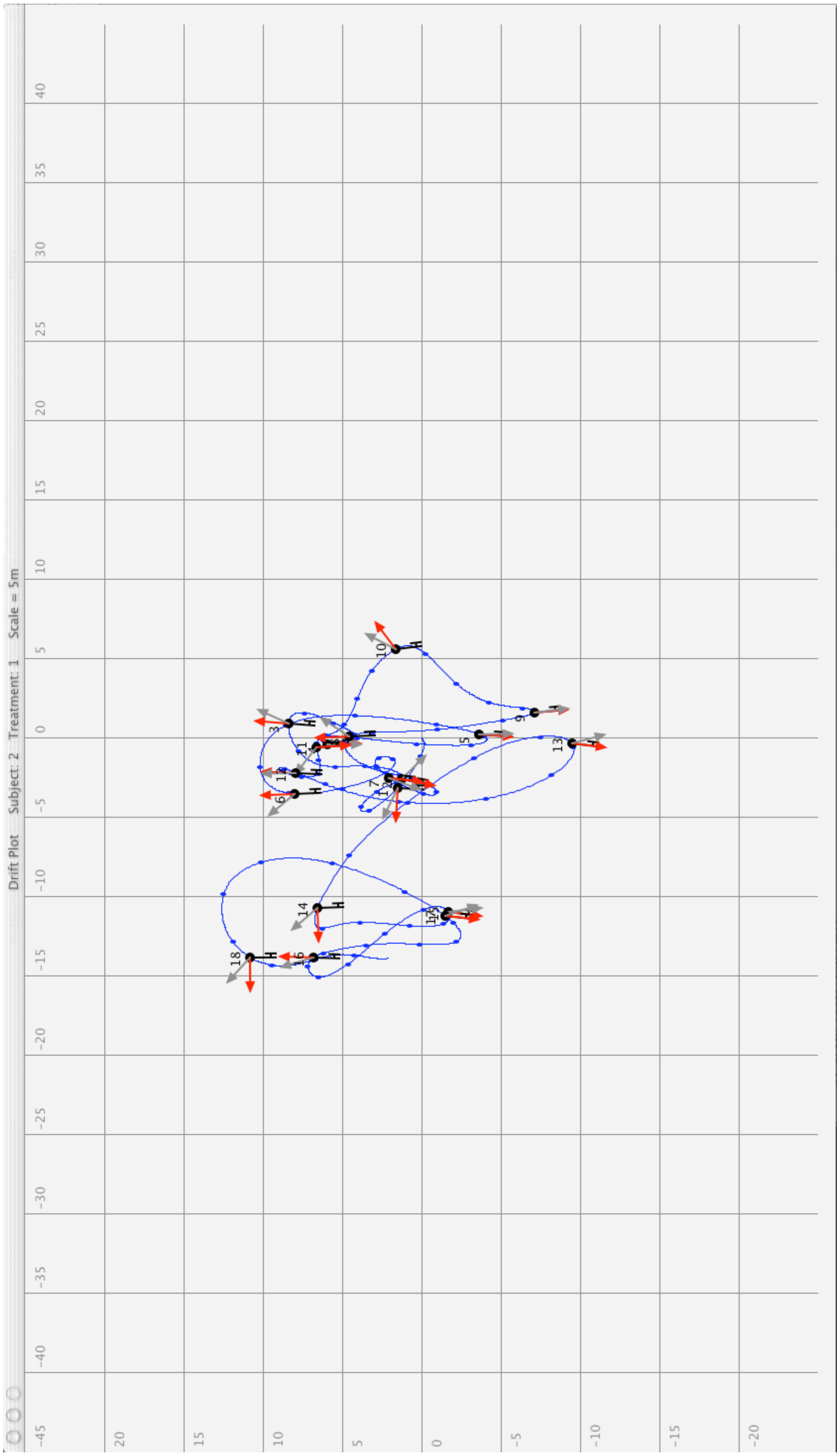
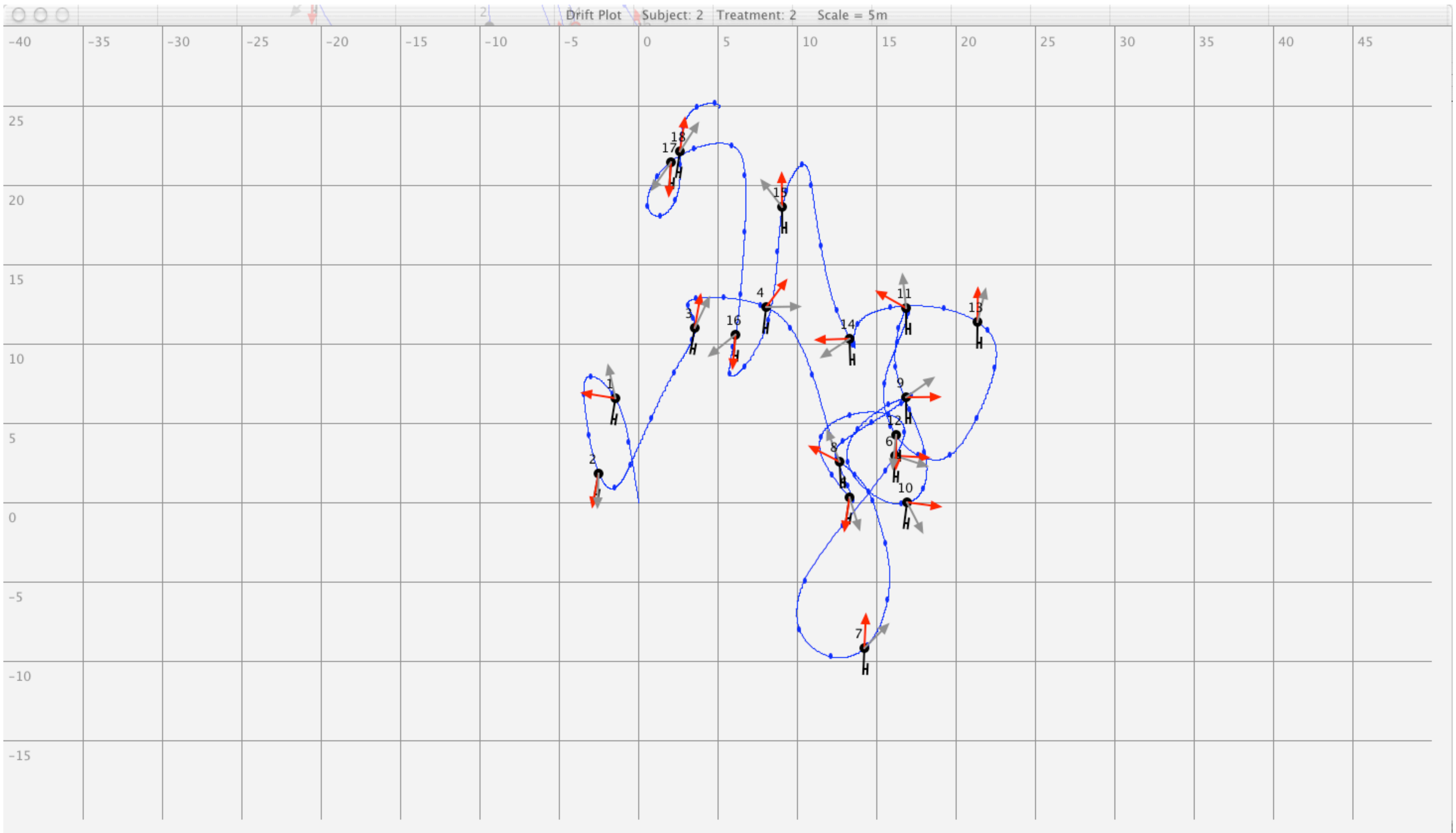
Subject 2




Drift Plot
Subject: 2
Treatment: 2
Scale = 5m
-40
-35
-30
-25
-20
-15
-10
-5
0
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15
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35
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45
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15
10
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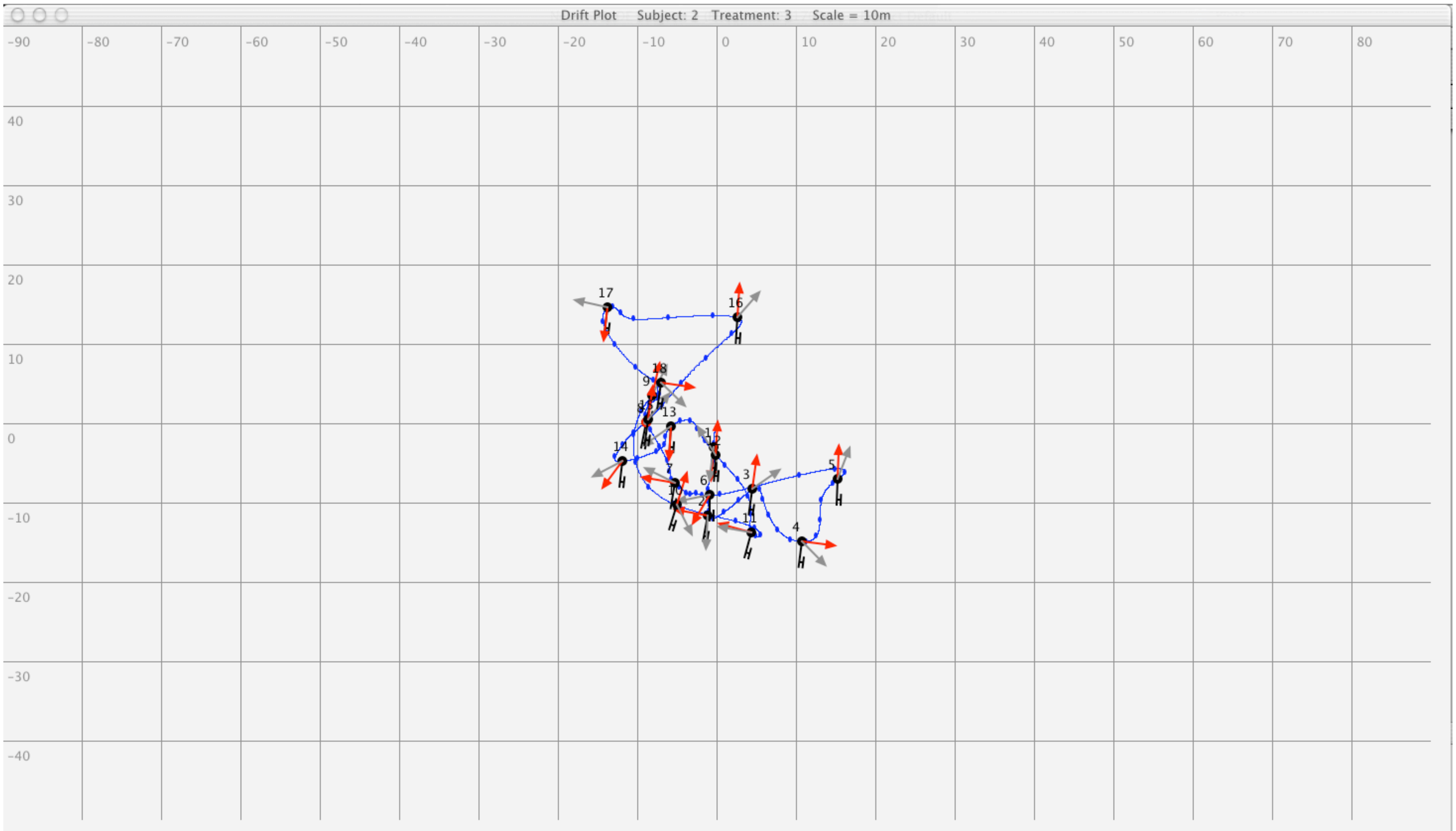
0
-5
-10
-15



Drift Plot
Subject: 2
Treatment: 3
Scale = 10m
-90
-80
-70
-60
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-40
-30
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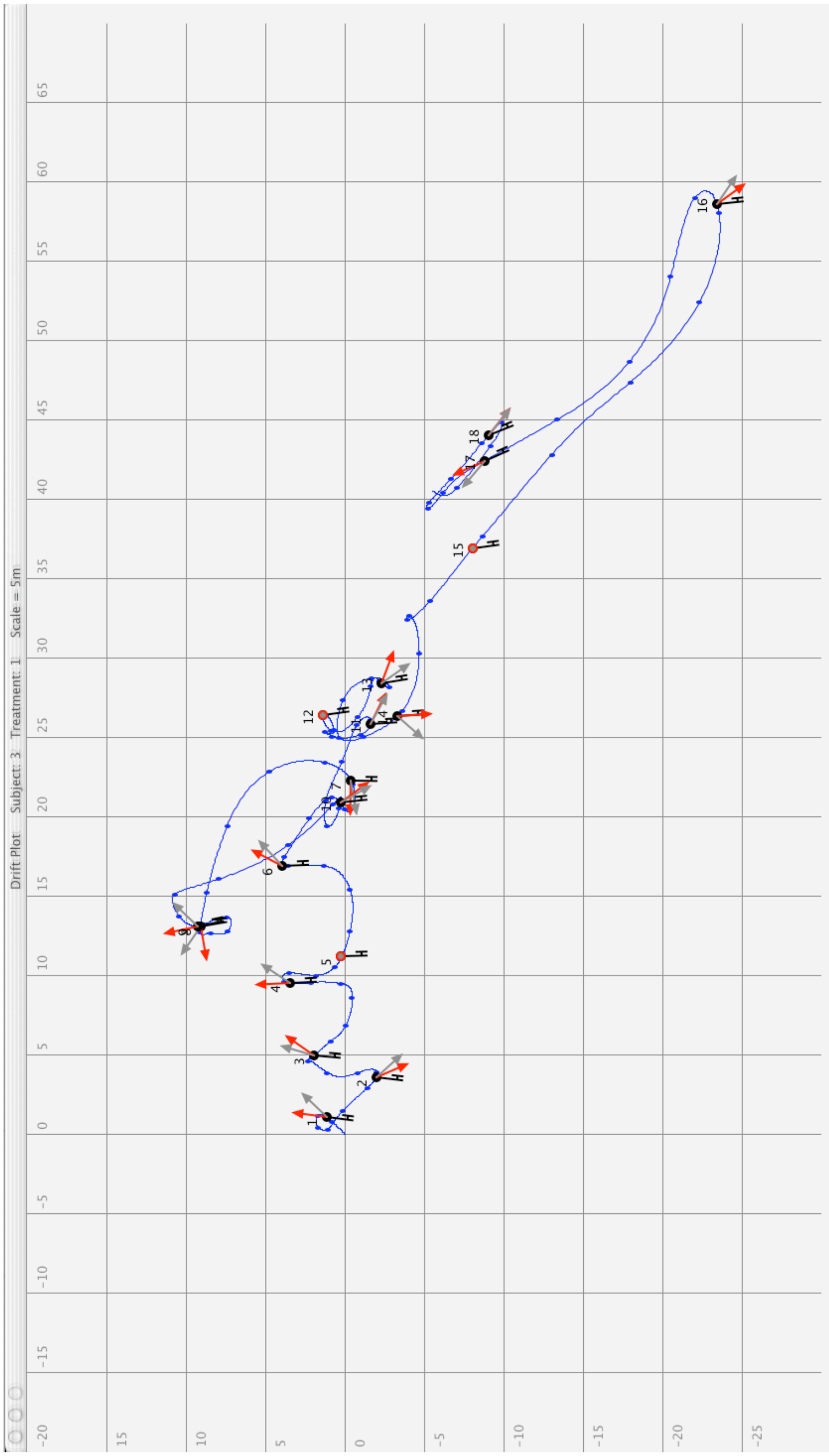
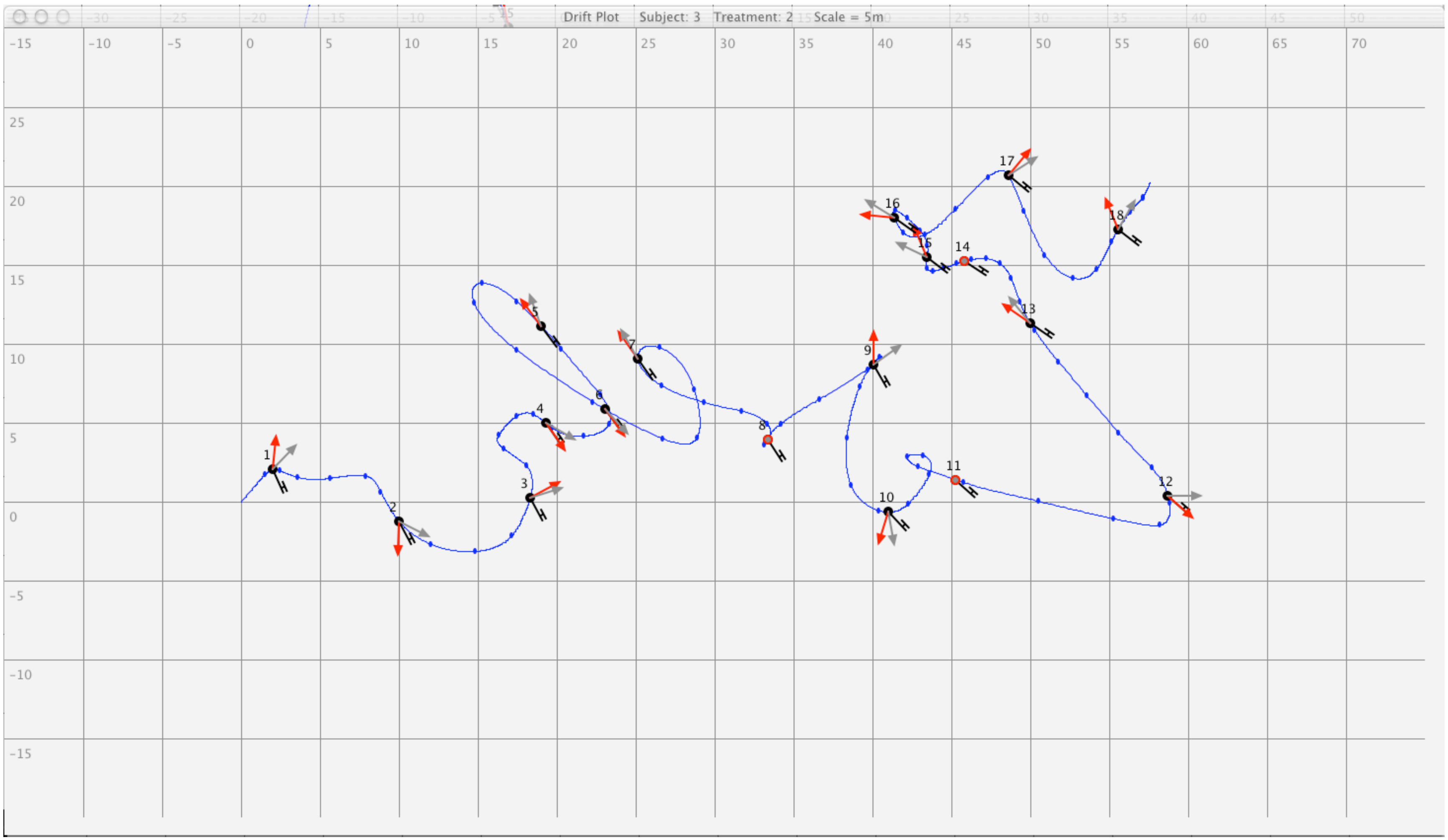
-10
-20
-30
-40

Subject 3




Drift Plot
Subject: 3
Treatment: 2
Scale = 5m
-15
-10
-5
0
5
10
15
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25
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35
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45
50
55
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65
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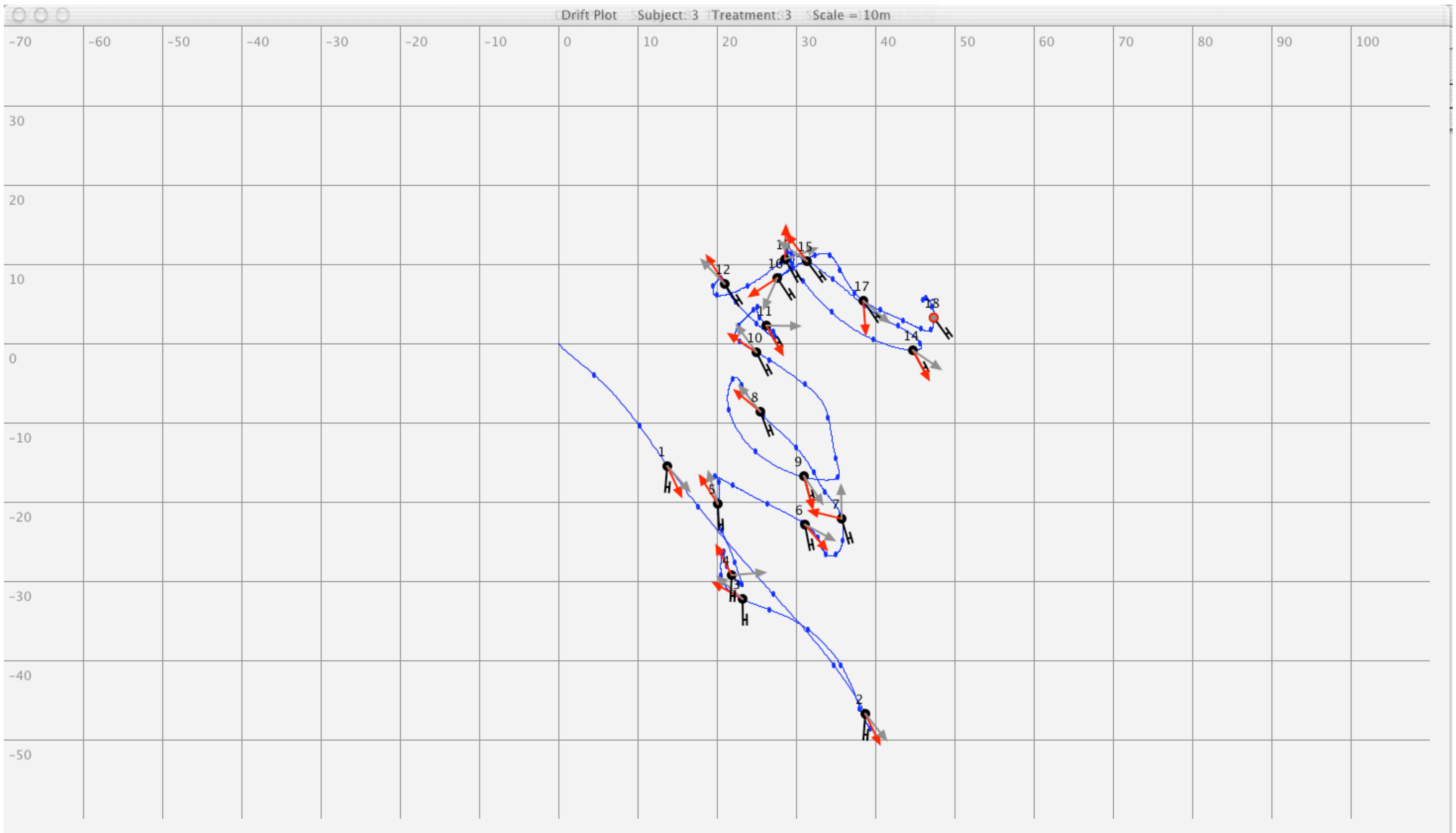
Drift Plot
Subject: 3
Treatment: 3
Scale = 10m
-70
-60
-50
-40
-30
-20
-10
0
10
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50
60
70
80
90
100
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20
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-10
-20
-30
-40
-50
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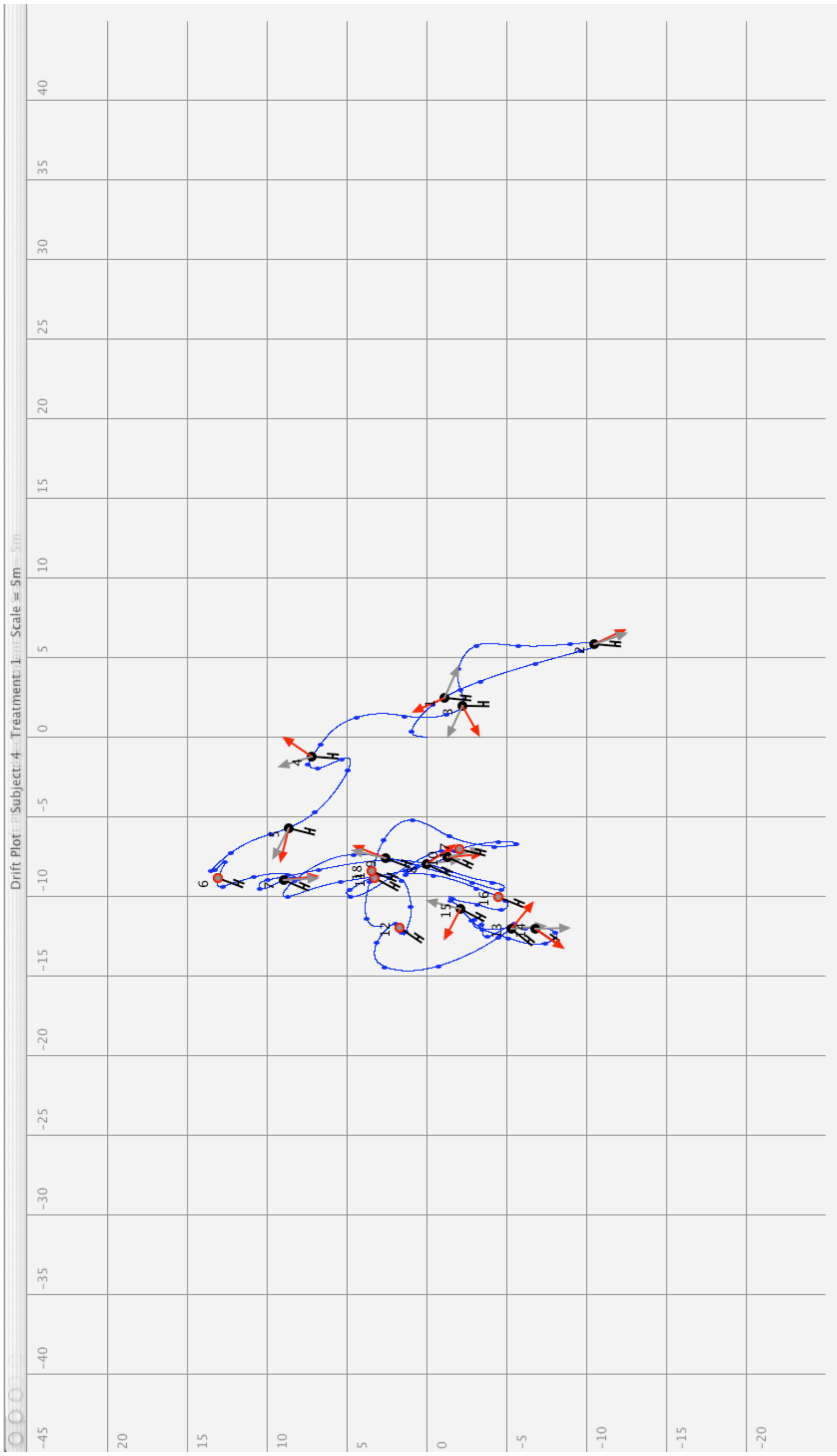
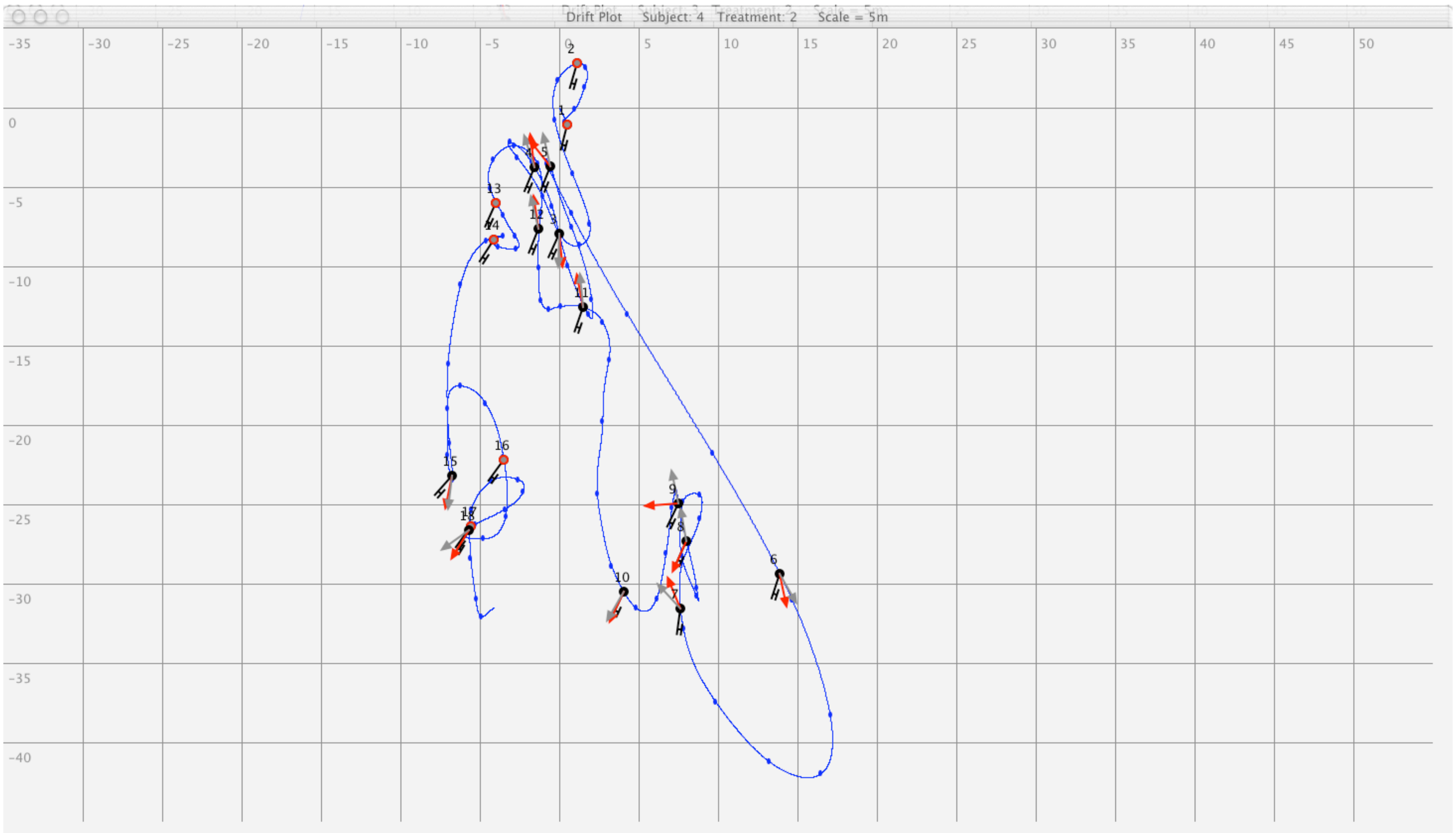
Subject 4





Drift Plot   Subject: 4   Treatment: 2   Scale = 5m
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
-40
1
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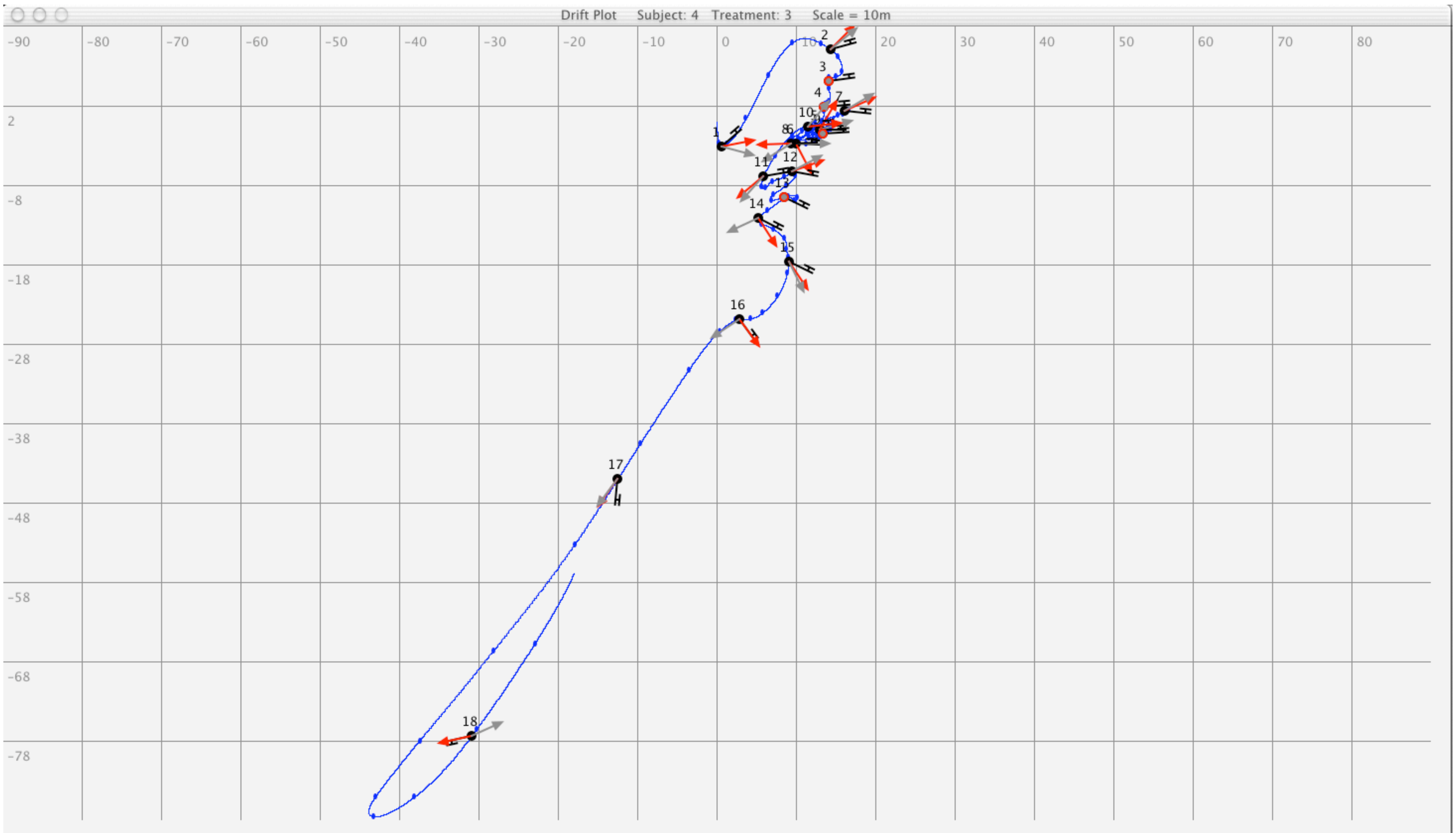

Drift Plot Subject: 4 Treatment: 3 Scale = 10m
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
2
-8
-18
-28
-38
-48
-58
-68
-78
1
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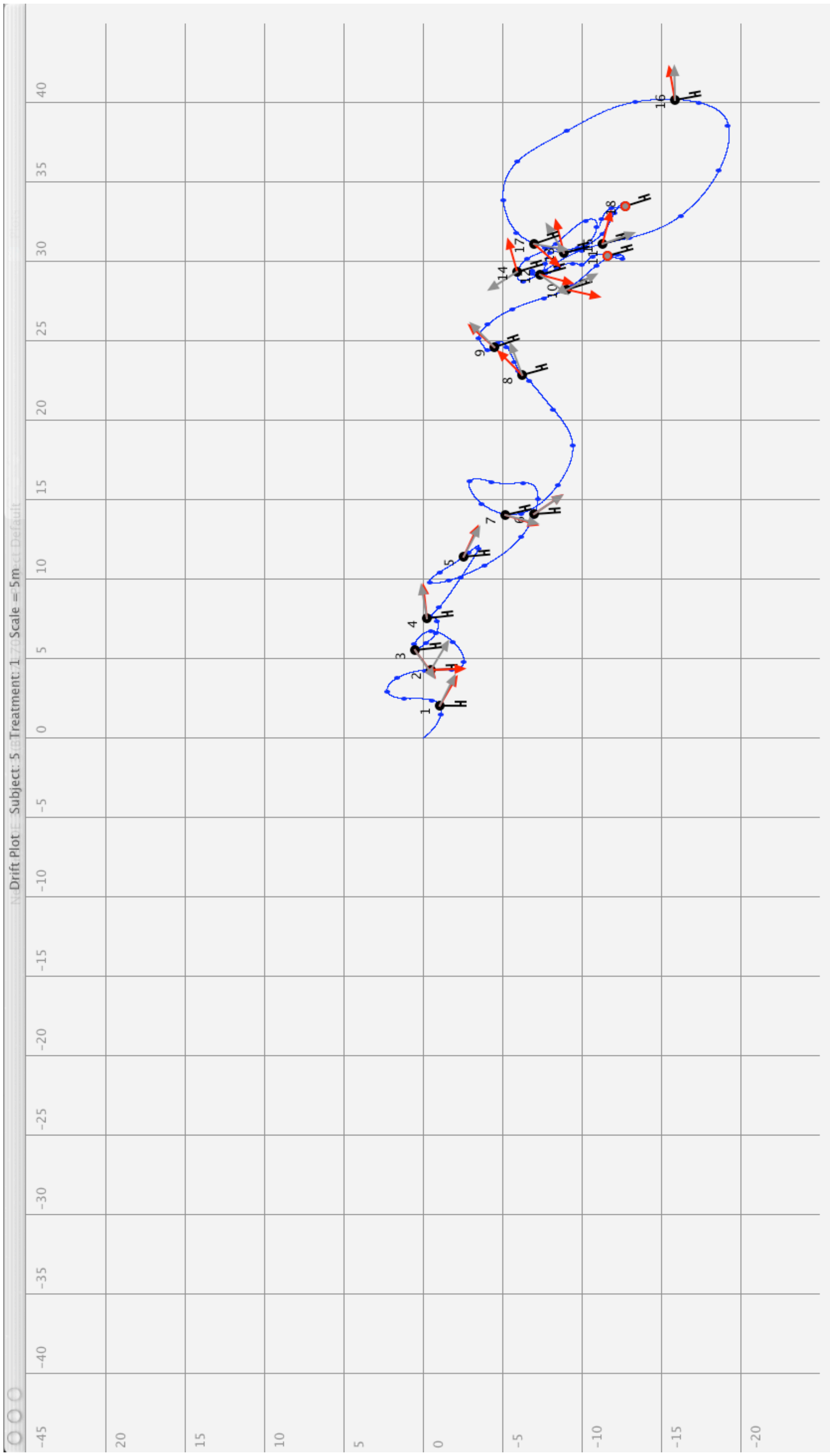
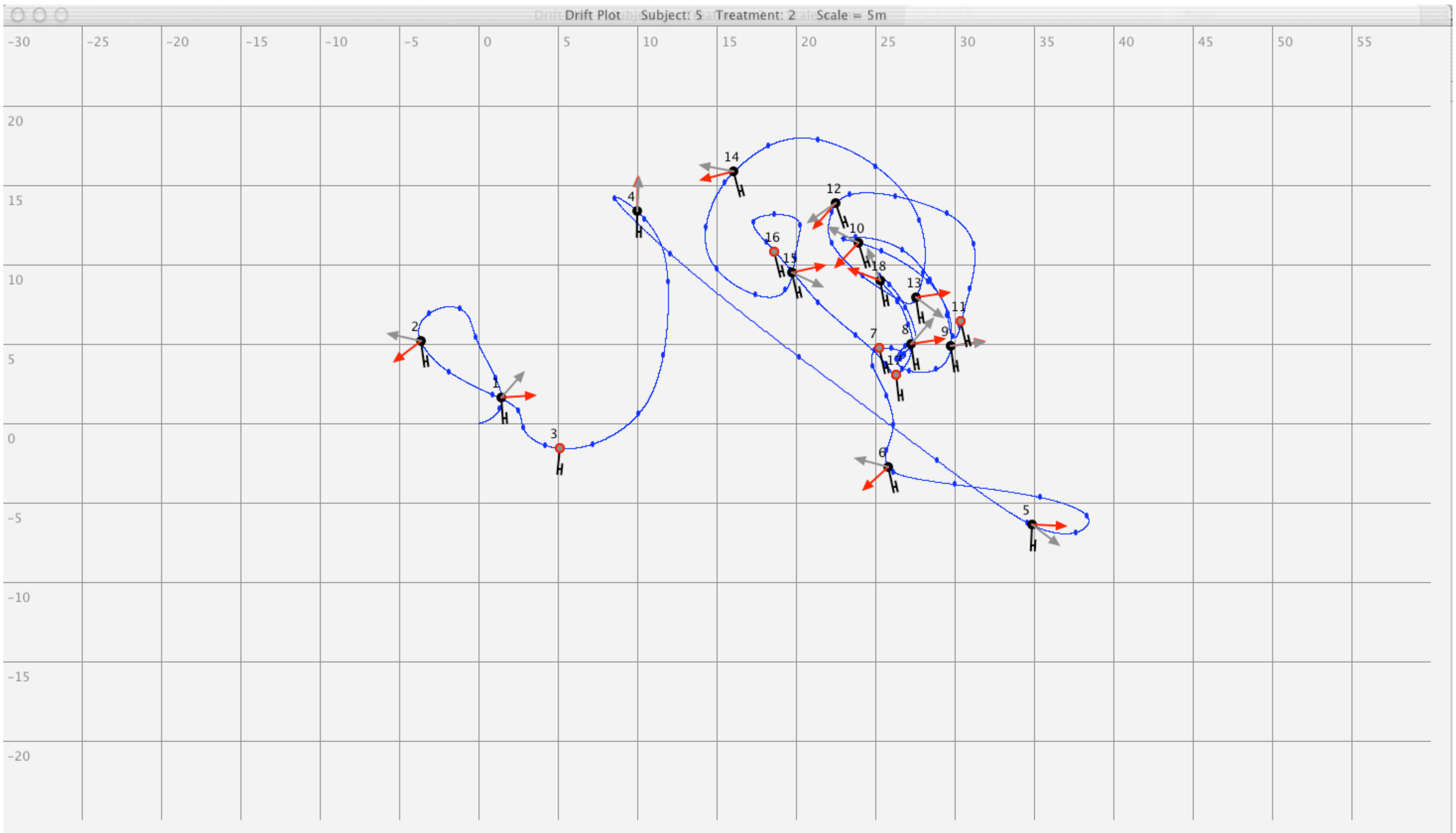
Subject 5





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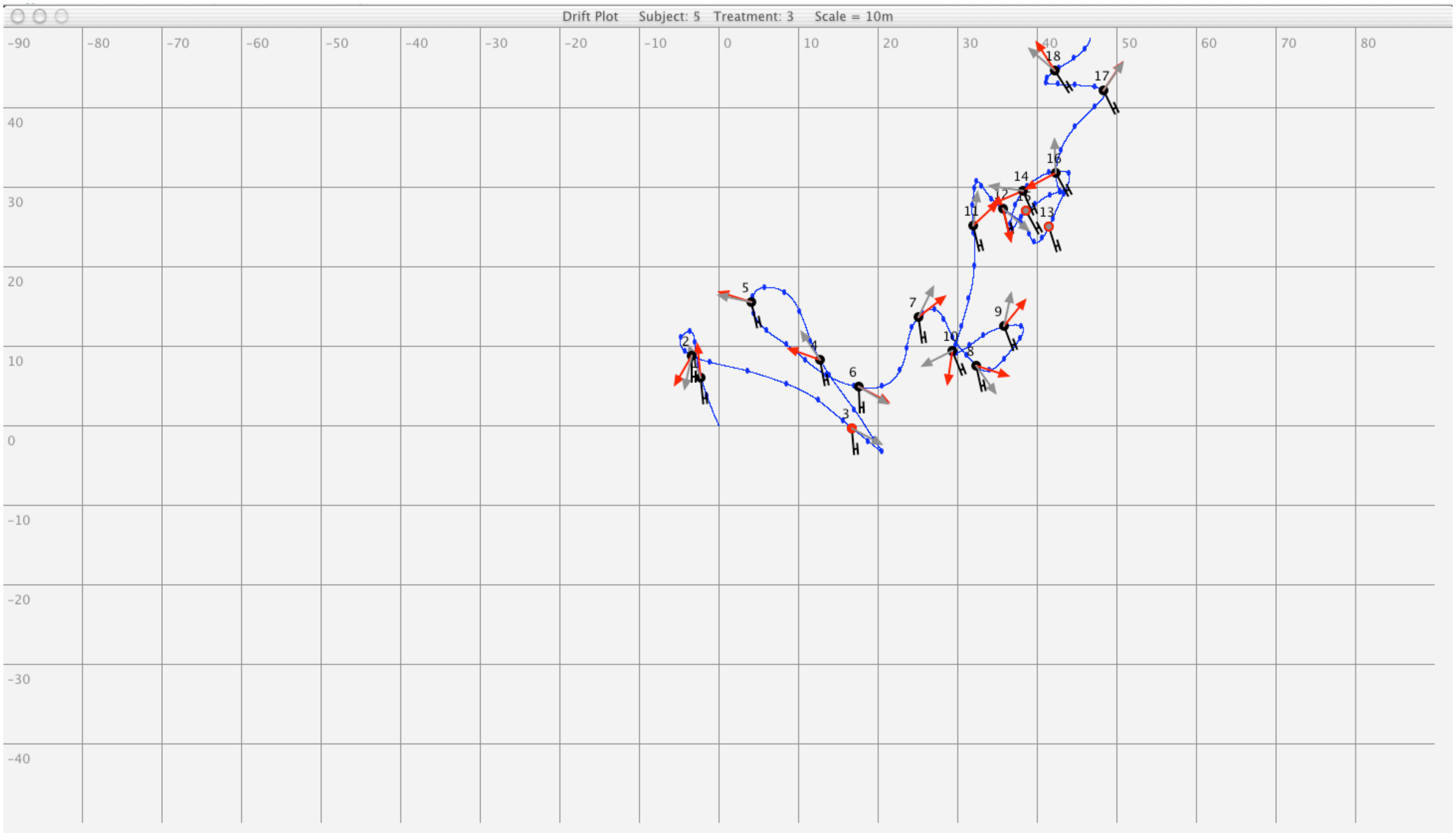
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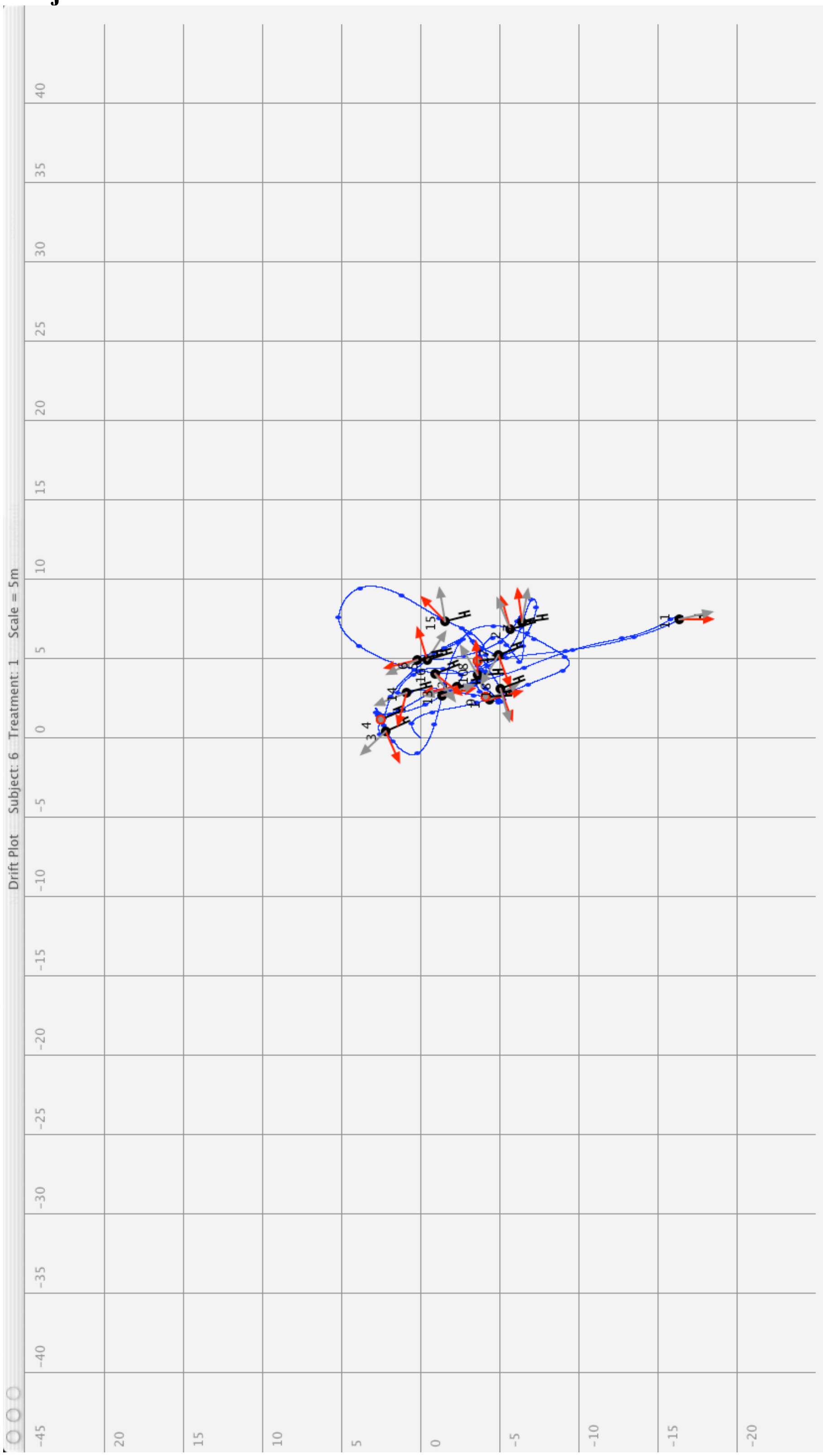
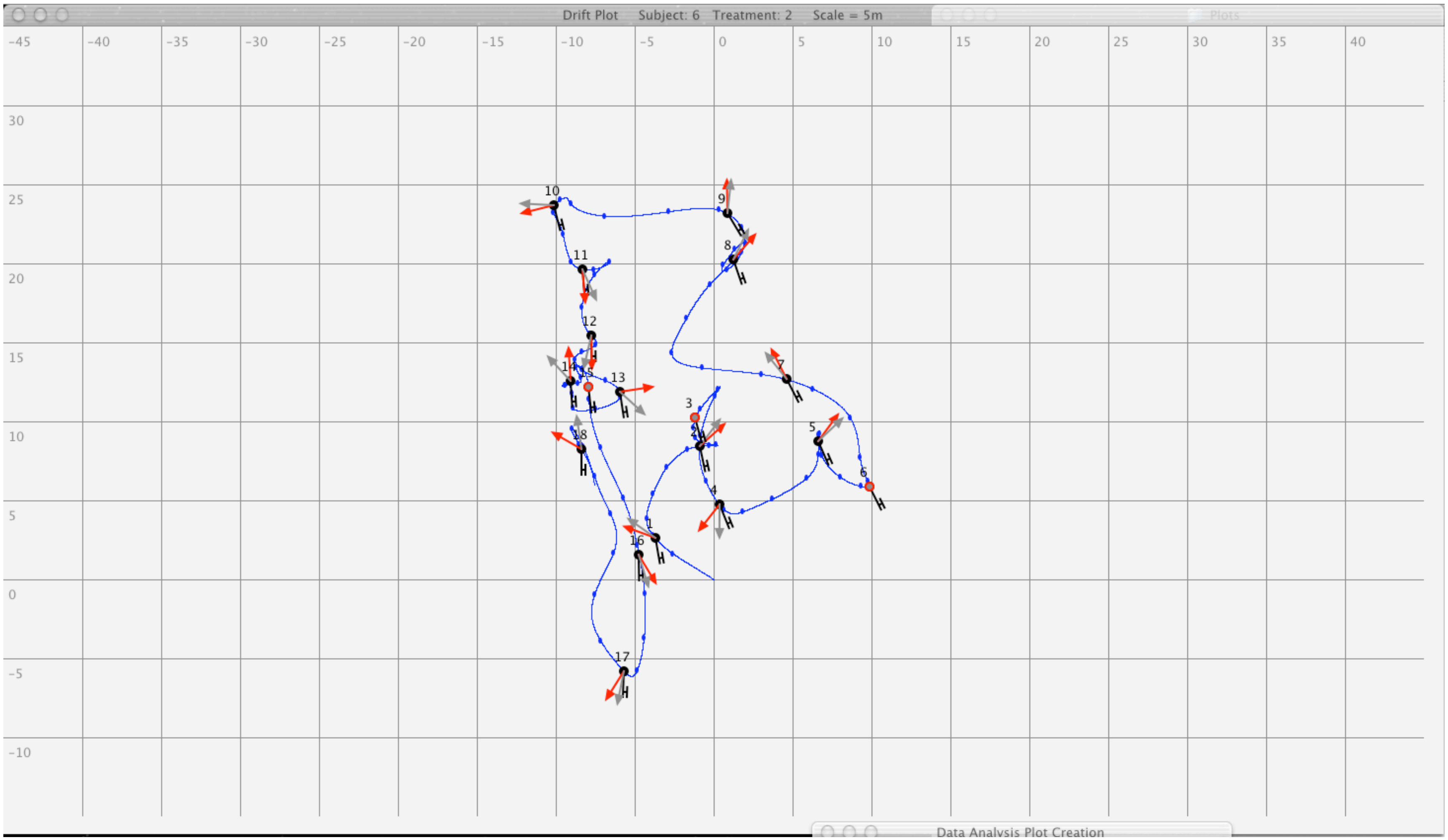
Subject 6

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-45
-40
-35
-30
-25
-20
-15
-10
-5
0
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15
20
25
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35
40
30
25
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-5
-10
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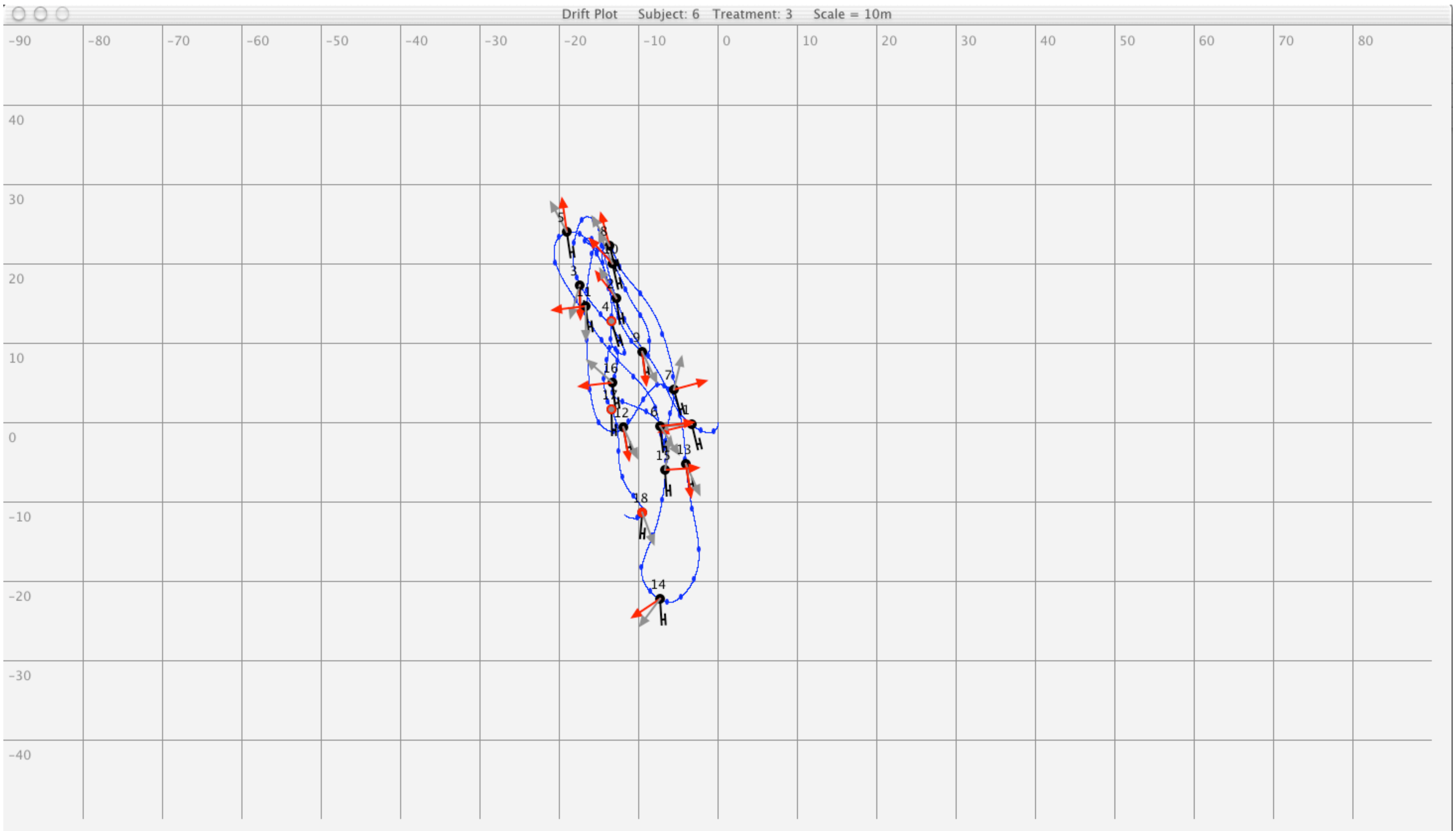
Data Analysis Plot Creation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-90
-80
-70
-60
-50
-40
-30
-20
-10
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70
80
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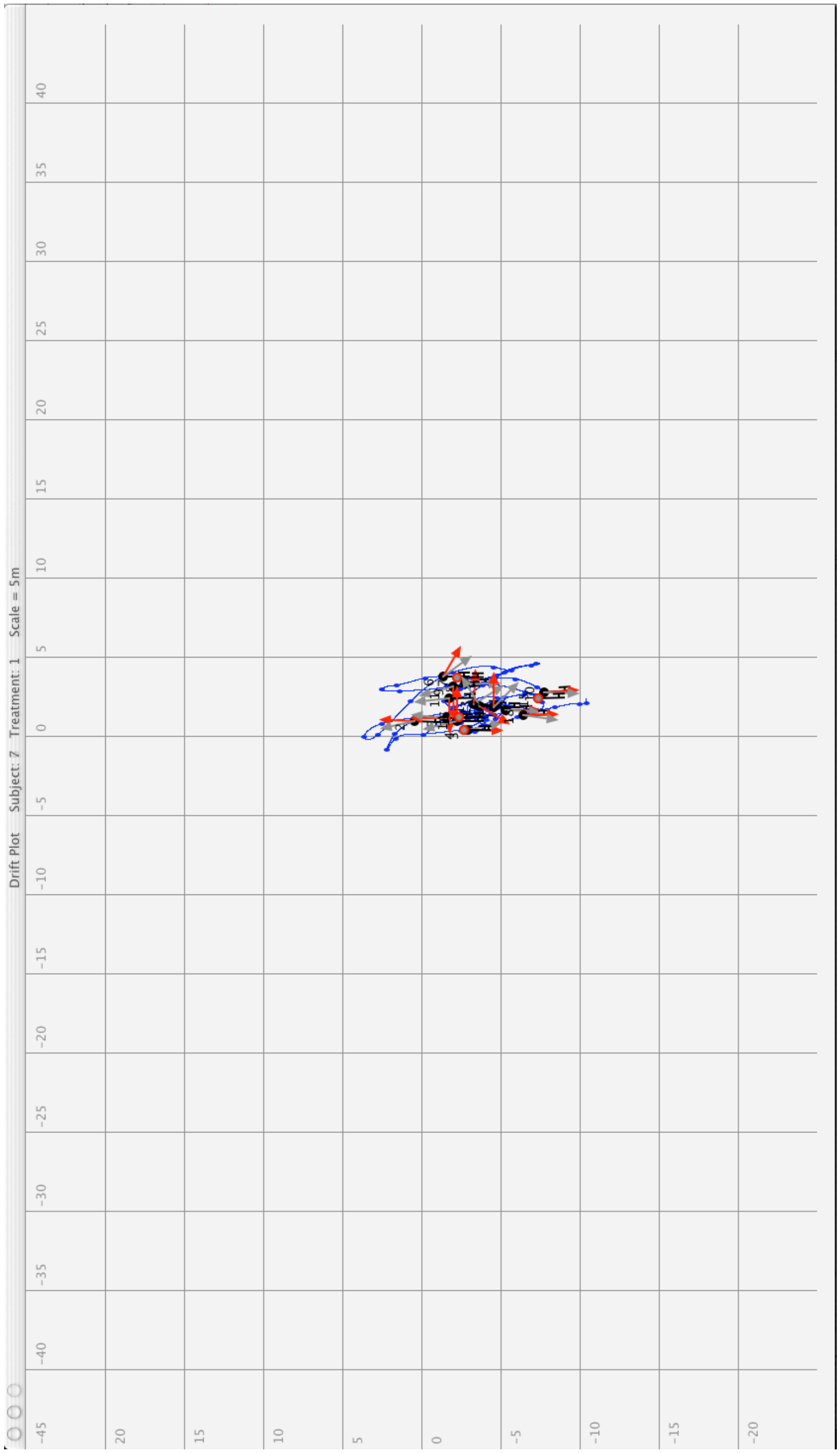
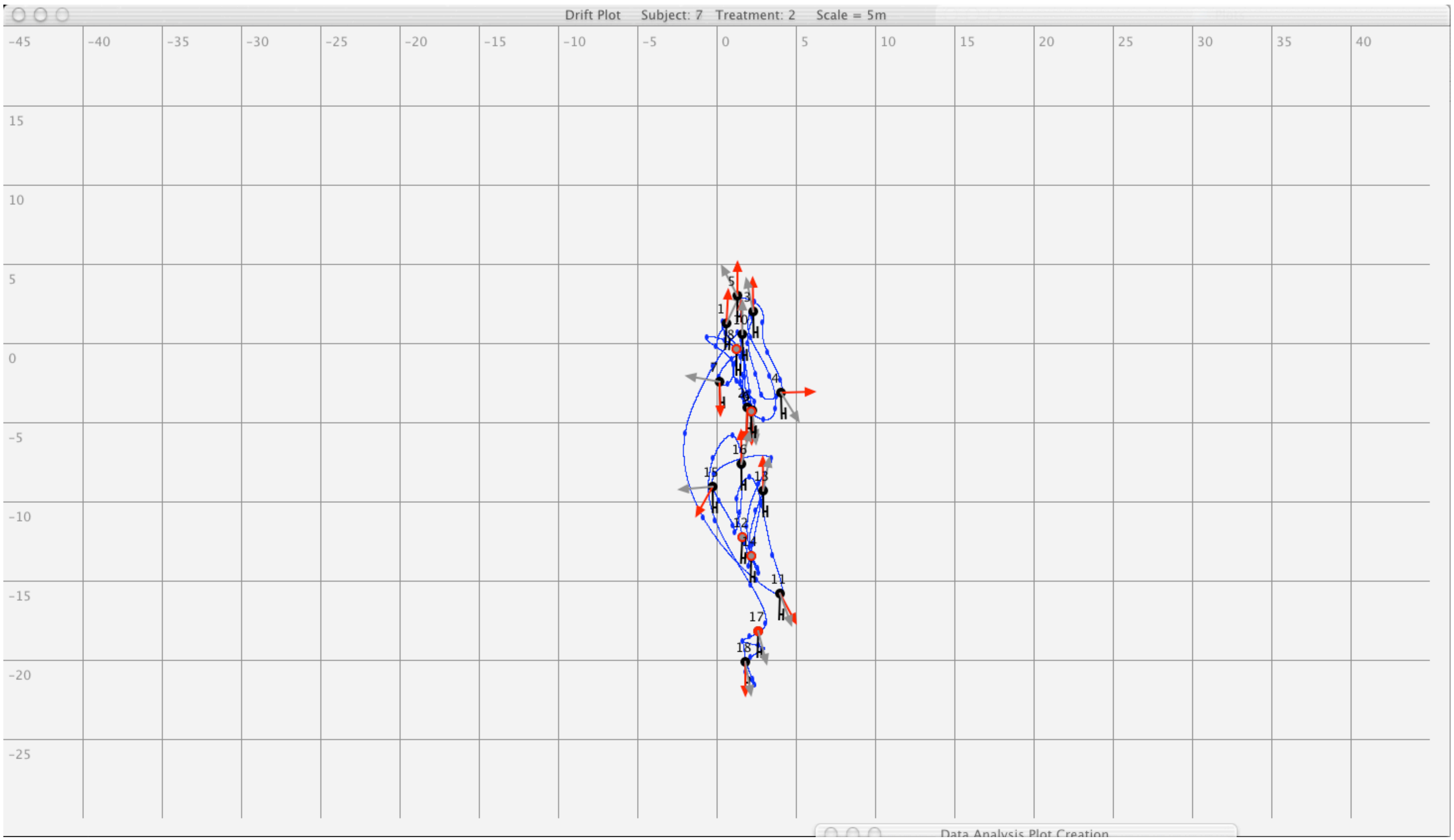
0
-10
-20
-30
-40

Subject 7




Drift Plot Subject: 7 Treatment: 2 Scale = 5m
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
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15
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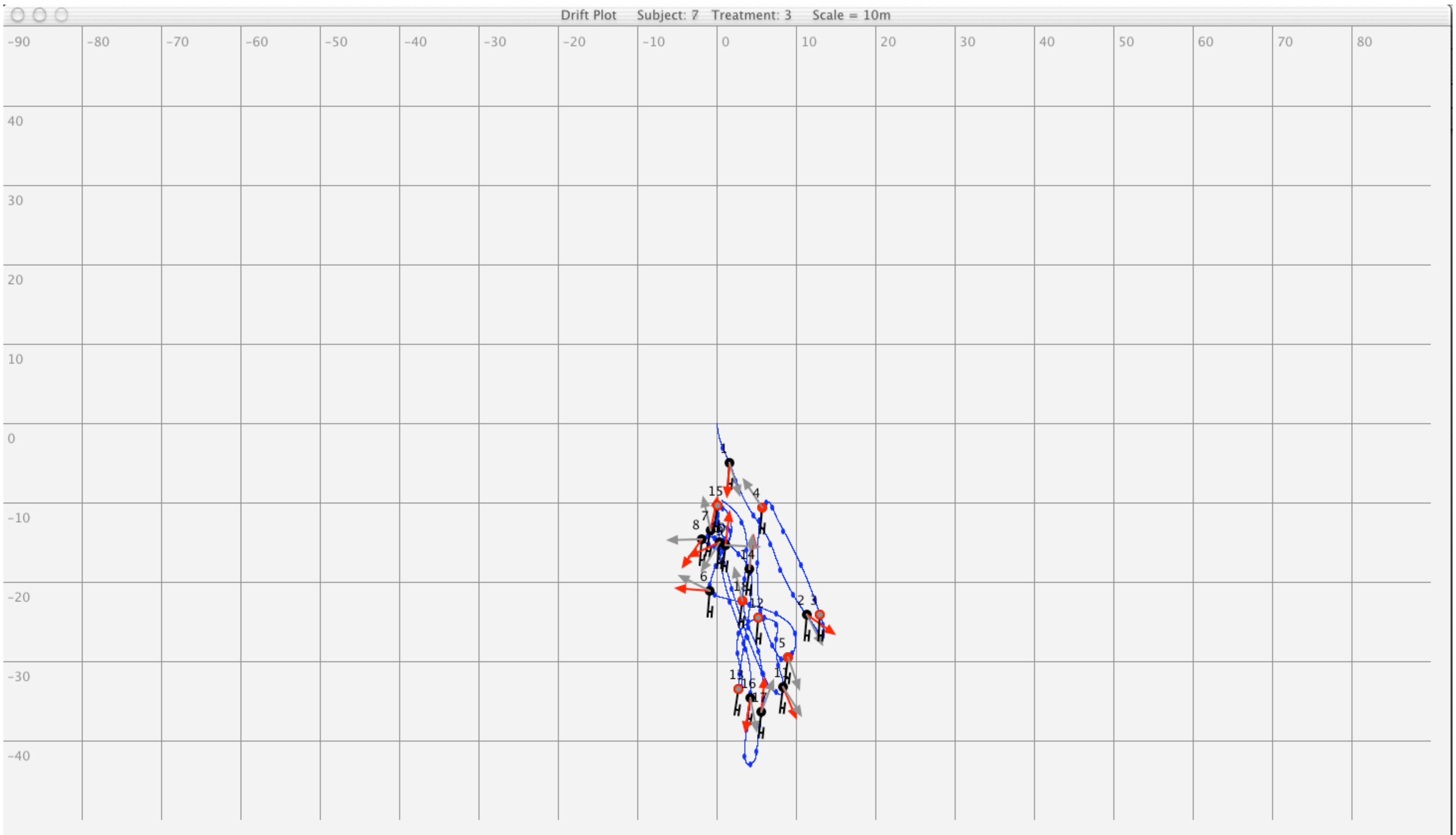
35
40
15
10
5
0
-5
-10
-15
-20
-25
Data Analysis Plot Creation



Drift Plot Subject: 7 Treatment: 3 Scale = 10m
-90
-80
-70
-60
-50
-40
-30
-20
-10
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80
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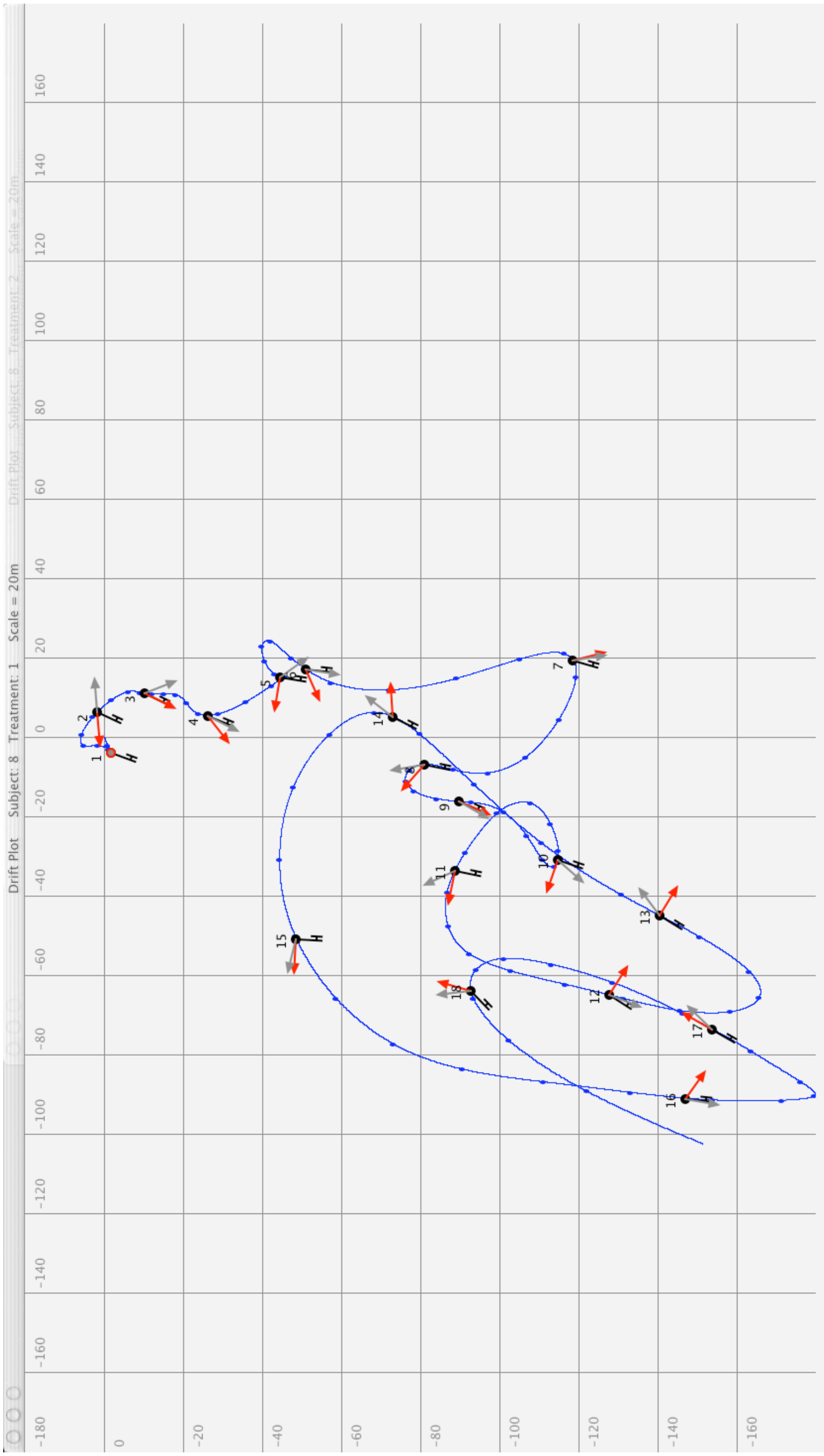
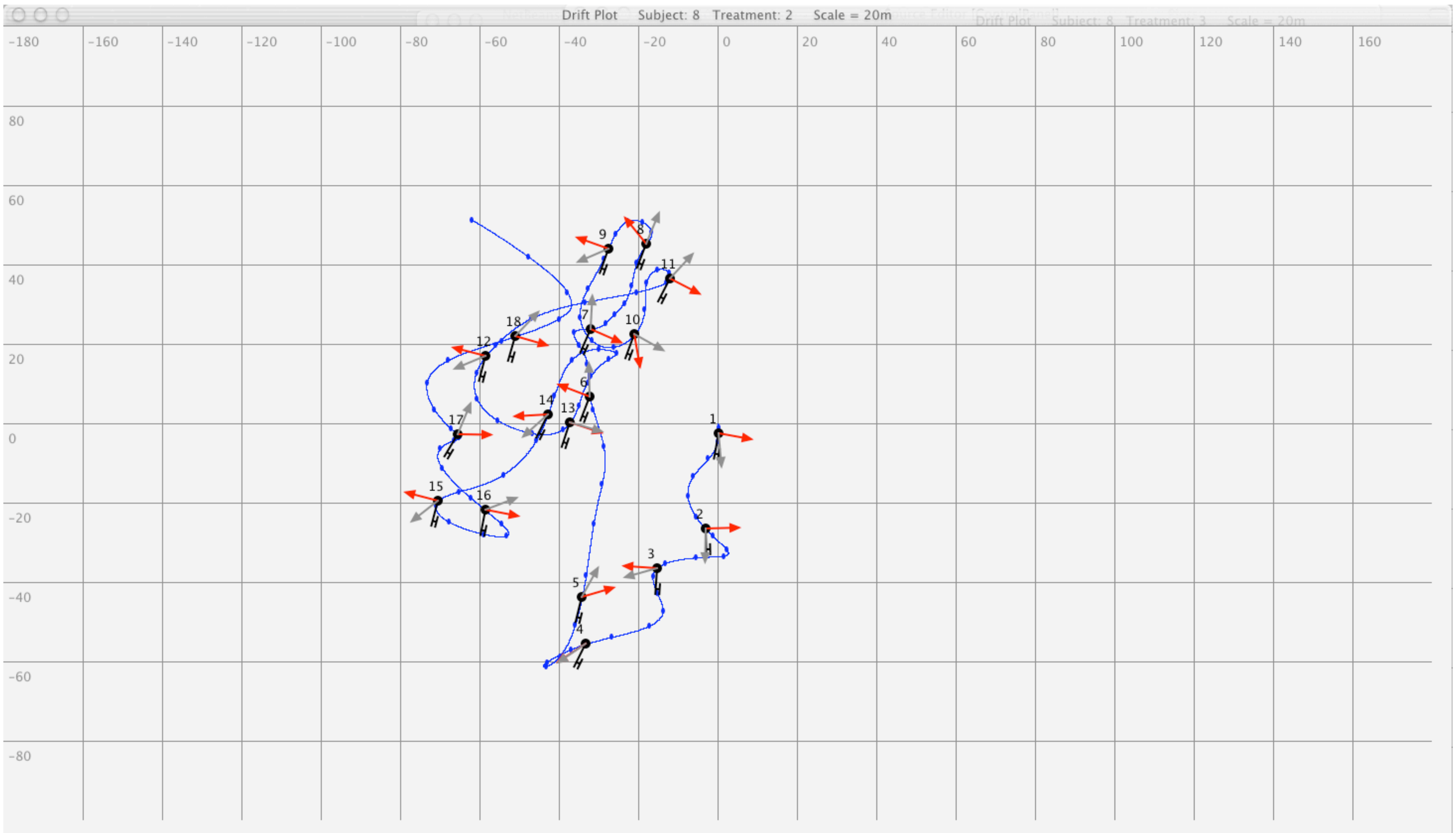
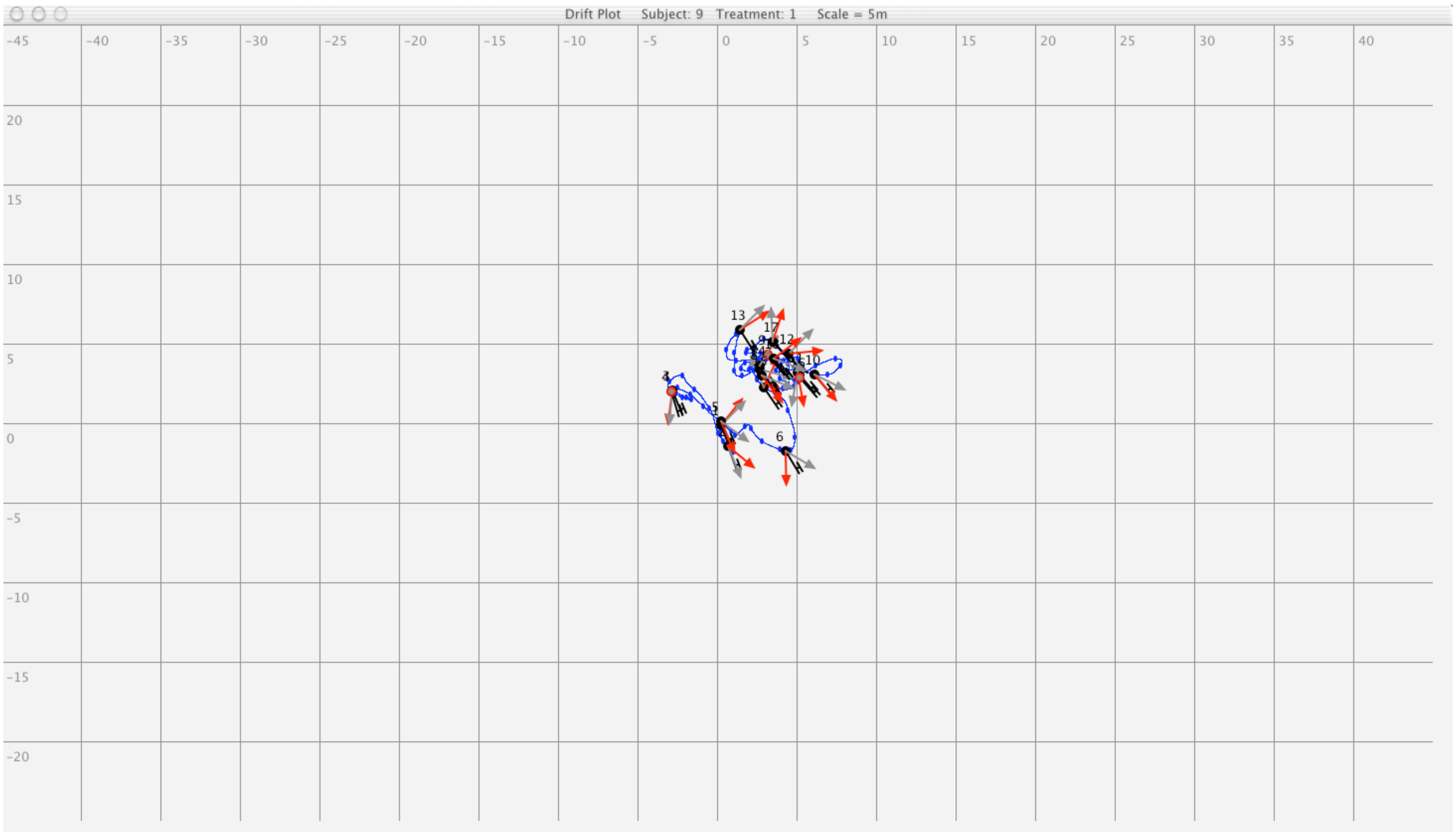
0
-10
-20
-30
-40

Subject 8

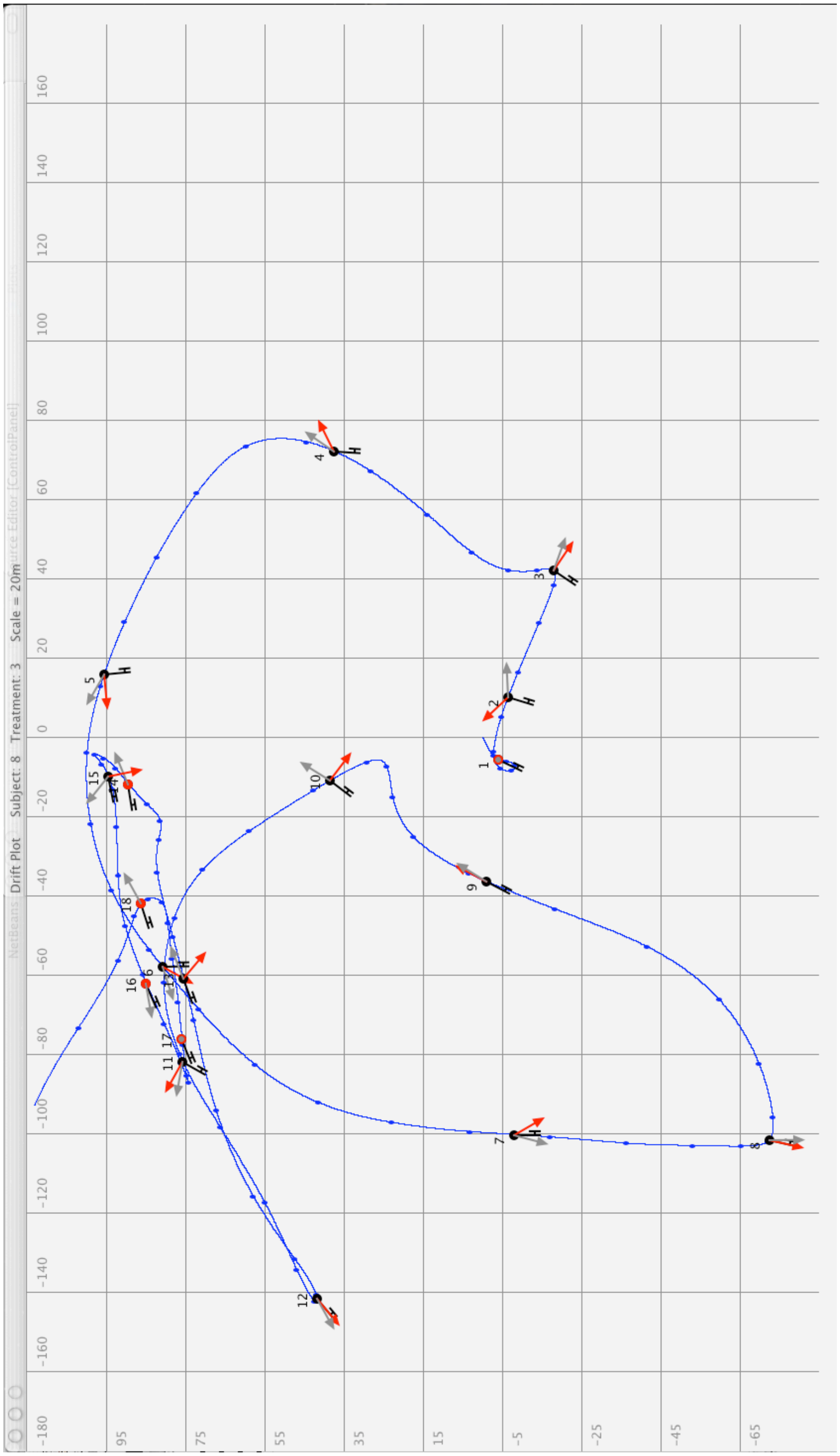




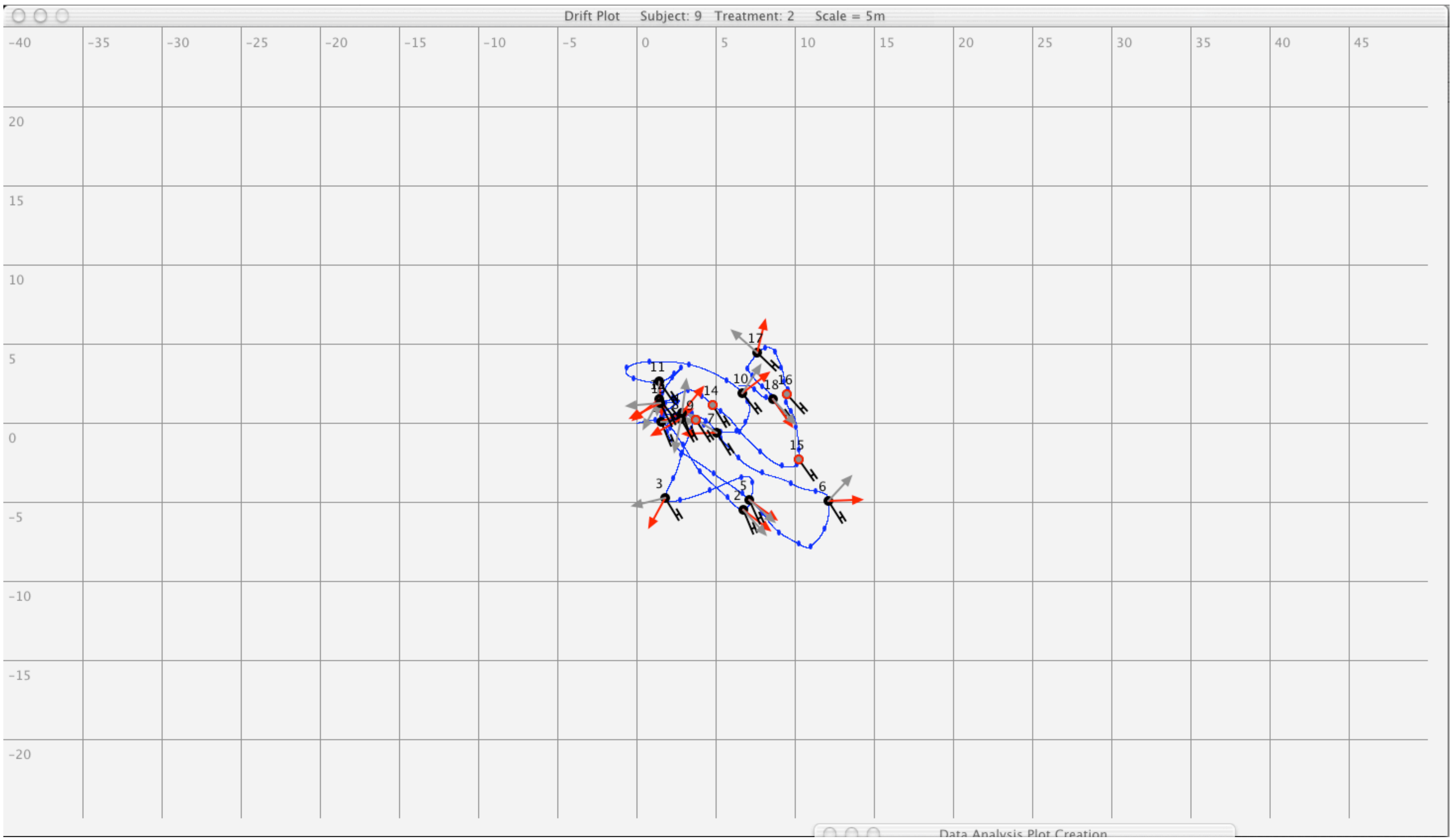
Drift Plot Subject: 8 Treatment: 2 Scale = 20m
-180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160
80 60 40 20 0 -20 -40 -60 -80
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

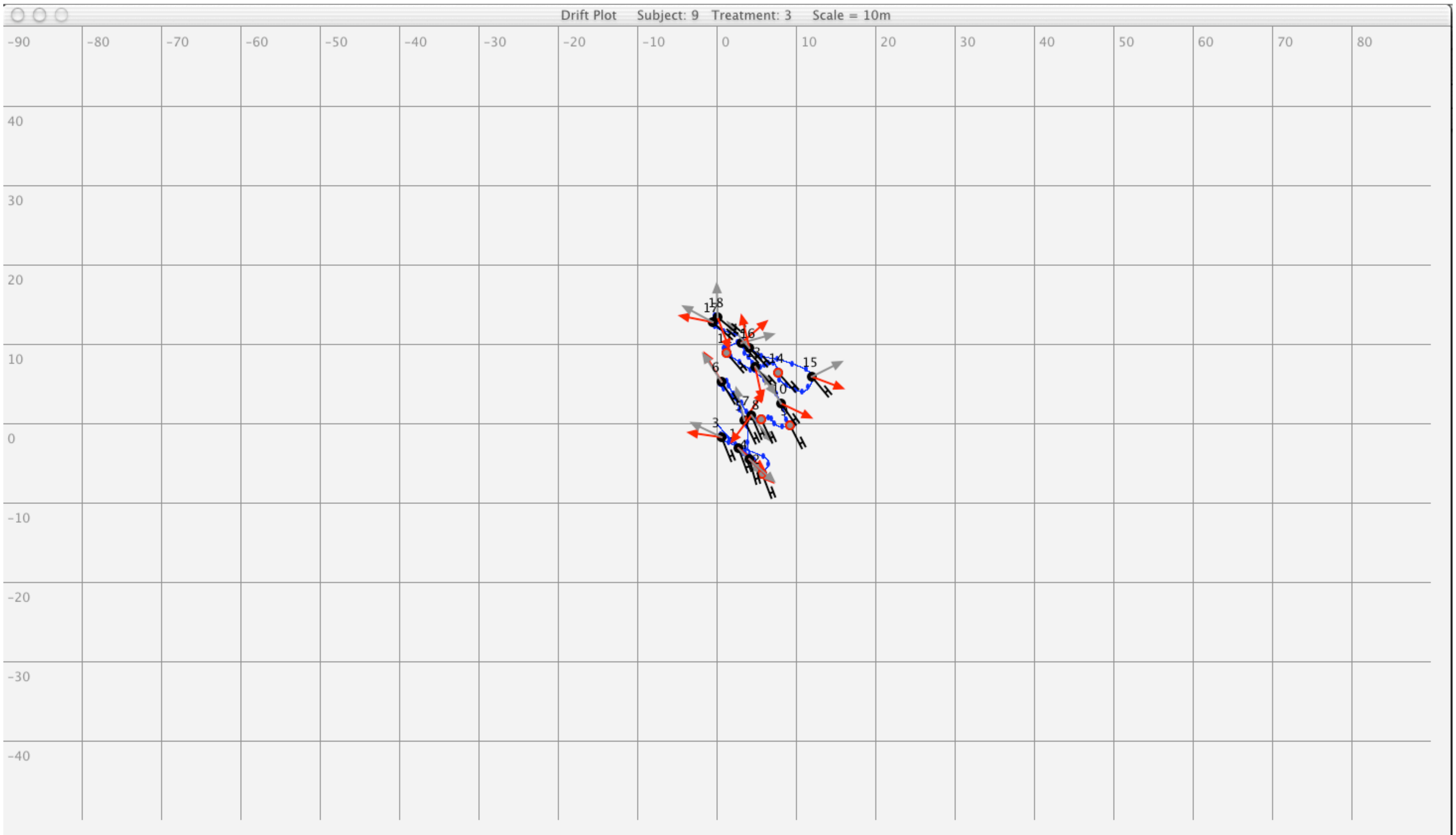

Drift Plot Subject: 9 Treatment: 1 Scale = 5m
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
20
15
10
5
0
-5
-10
-15
-20
13
17
12
10
6
5

Subject 9

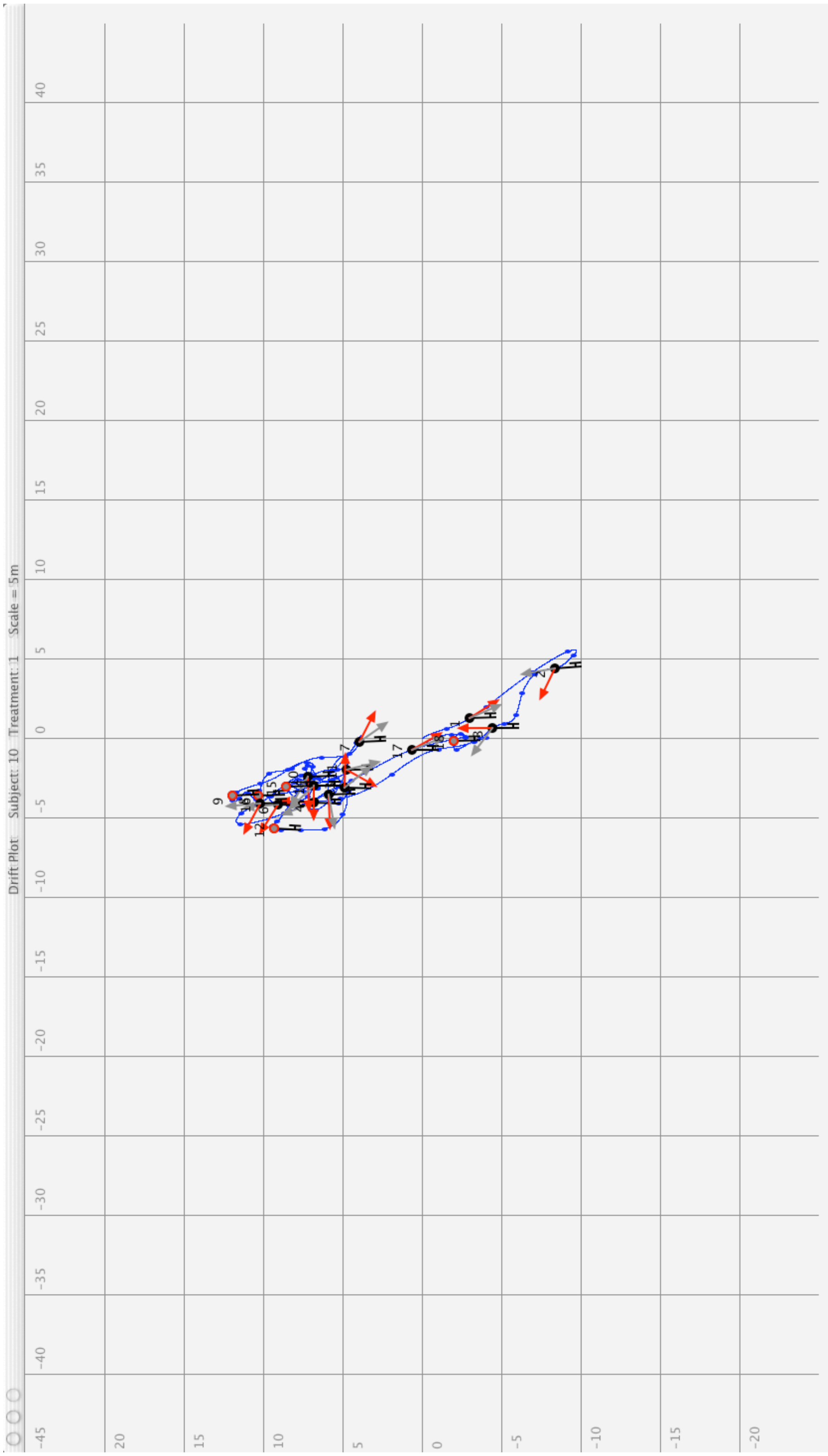


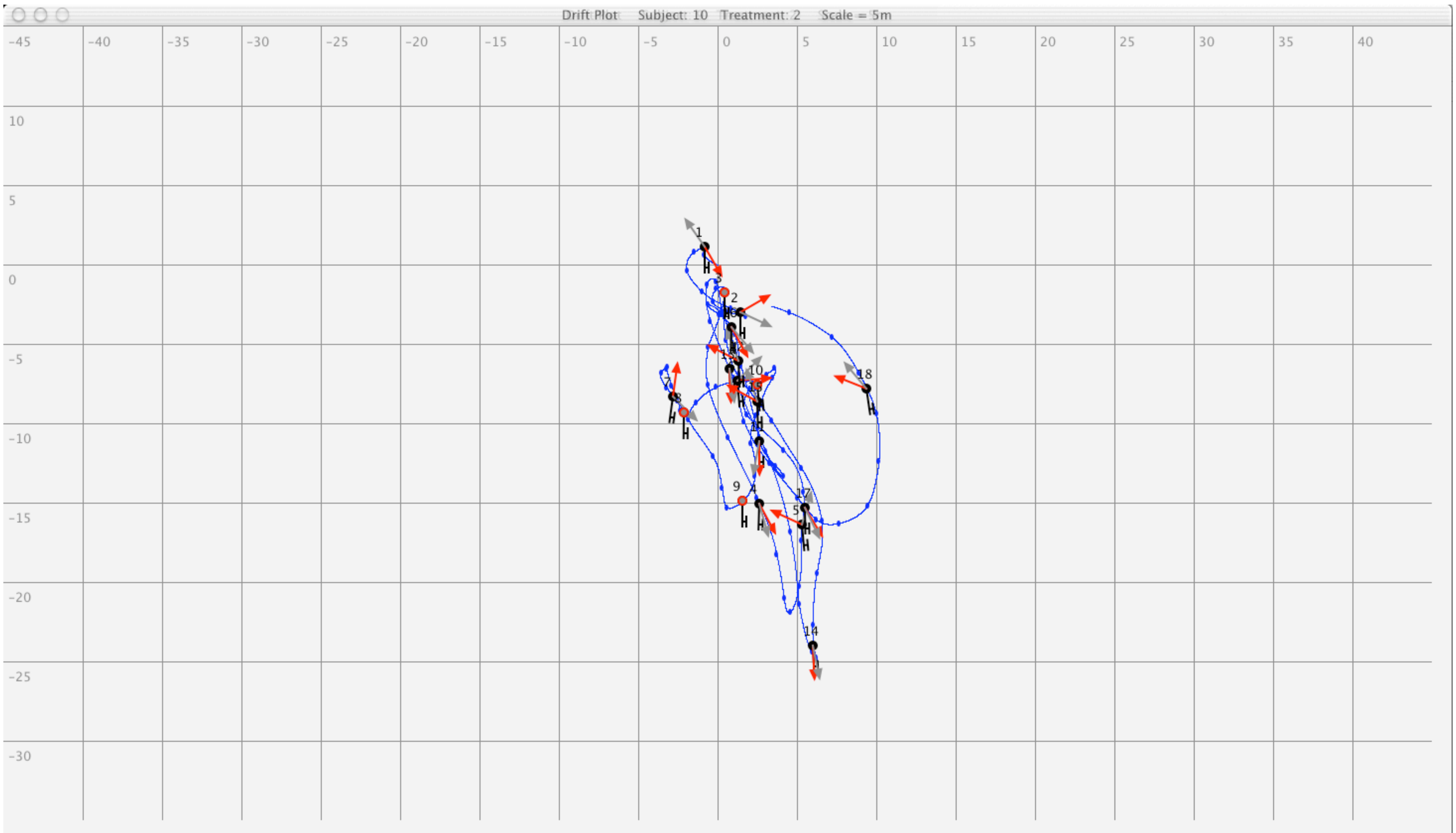
Drift Plot
Subject: 8
Treatment: 3
Scale = 20m
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
95
75
55
35
15
-5
-25
-45
-65

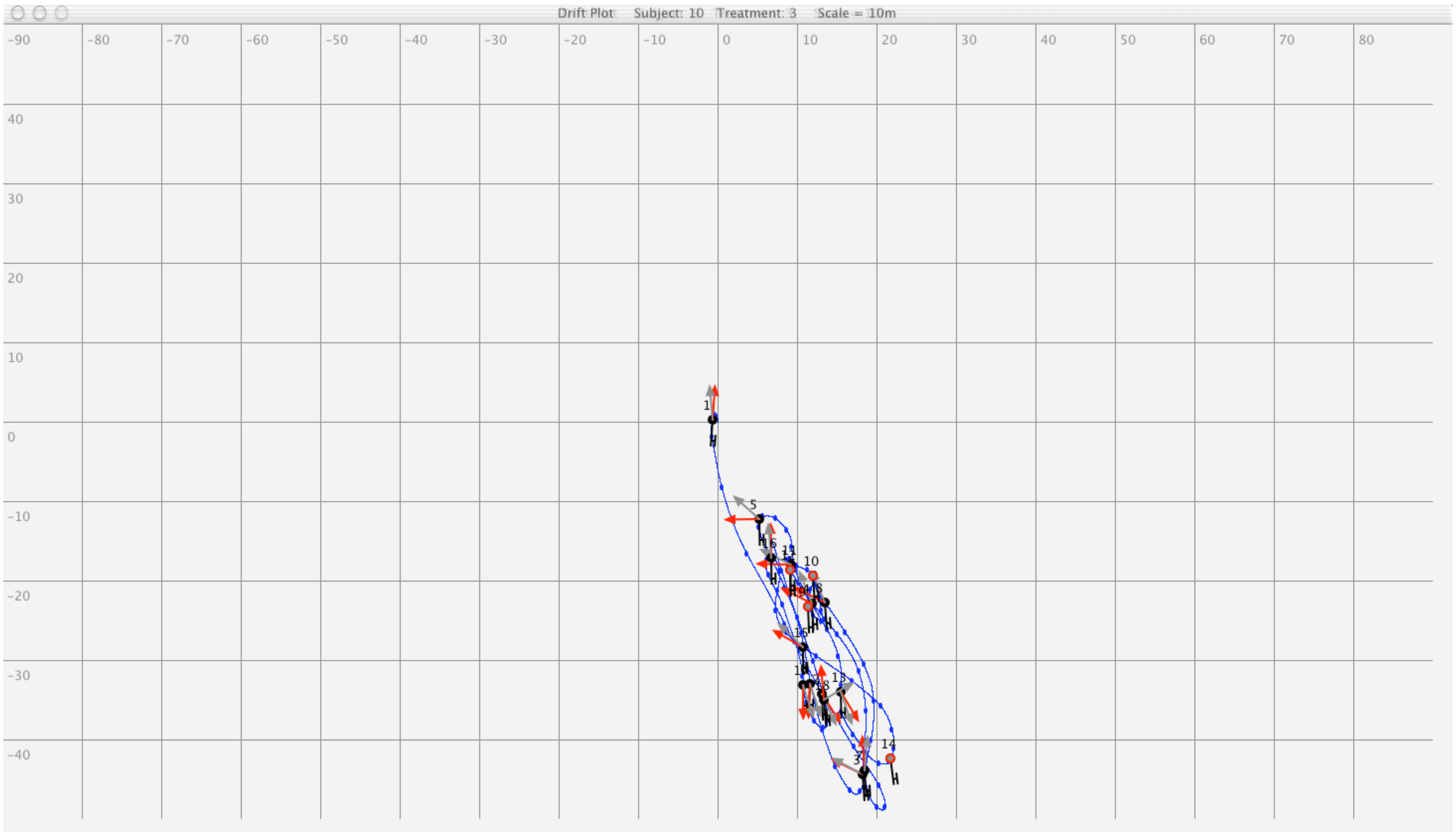

Drift Plot Subject: 9 Treatment: 2 Scale = 5m
-40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45
20 15 10 5 0 -5 -10 -15 -20
Data Analysis Plot Creation


Drift Plot Subject: 9 Treatment: 3 Scale = 10m
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
40
30
20
10
0
-10
-20
-30
-40
18
16
14
15
10
8
7
6
3
1

Subject 10




Drift Plot Subject: 10 Treatment: 2 Scale = 5m
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
10
5
0
-5
-10
-15
-20
-25
-30


Drift Plot
Subject: 10
Treatment: 3
Scale = 10m
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
40
30
20
10
0
-10
-20
-30
-40
1
5
10
14
3

APPENDIX F SIM-SICKNESS QUESTIONNAIRE DATA

EFFECTS (AFTER - BEFORE)

D	E	F	G	H	I	J	K	L	M	N
	1	2	3	4	5	6	7	8	9	10
General Discomfort		0	0	0	0	1	0	0	0	0
Fatigue		0	0	0	0	0	0	0	0	0
Headache		0	0	0	0	0	0	0	0	0
Eye Strain		0	0	0	0	0	0	0	0	0
Difficulty Focusing		0	0	0	0	0	0	0	0	0
Increased Salivation		0	0	0	0	0	0	0	1	0
Sweating		0	0	0	0	0	0	0	0	0
Nausea		0	0	0	0	1	0	0	0	0
Difficulty Concentrating		0	0	0	0	0	0	0	0	0
Fullness of Head		0	0	0	0	0	0	0	0	0
Blurred Vision		0	0	0	0	0	0	0	0	0
Dizzy(Eyes Open)		0	0	0	0	1	0	0	0	0
Dizzy(Eyes Closed)		0	0	0	0	0	0	0	0	0
Vertigo		0	0	0	0	0	0	0	0	0
Stomach Awareness		0	0	0	0	0	0	0	0	0
Burping		0	0	0	0	0	0	0	0	0
	1	2	3	4	5	6	7	8	9	10
Nausea	0.00	0.00	0.00	0.00	0.00	19.08	0.00	0.00	9.54	0.00
Oculomotor	0.00	0.00	0.00	0.00	0.00	7.58	0.00	0.00	0.00	0.00
Disorientation	0.00	0.00	0.00	0.00	0.00	27.84	0.00	0.00	0.00	0.00
Total	0.00	0.00	0.00	0.00	0.00	18.70	0.00	0.00	3.74	0.00

BEFORE

	1	2	3	4	5	6	7	8	9	10
General Discomfort		0	0	0	0	0	1	0	0	0
Fatigue		1	0	0	0	0	0	0	0	1
Headache		0	0	0	0	0	0	0	0	0
Eye Strain		1	0	0	0	0	0	0	1	0
Difficulty Focusing		0	0	0	0	0	0	0	0	1
Increased Salivation		0	0	0	0	0	0	0	0	0
Sweating		1	0	0	0	0	0	0	0	0
Nausea		0	0	0	0	0	0	0	0	0
Difficulty Concentrating		0	0	0	0	0	0	0	0	0
Fullness of Head		0	0	0	0	0	0	0	0	0
Blurred Vision		0	0	0	0	0	0	0	0	0
Dizzy(Eyes Open)		0	0	0	0	0	0	0	0	0
Dizzy(Eyes Closed)		0	0	0	0	0	0	0	0	0
Vertigo		0	0	0	0	0	0	0	0	0
Stomach Awareness		0	0	0	0	0	1	0	0	0
Burping		0	0	0	0	0	1	0	0	0

	1	2	3	4	5	6	7	8	9	10
Nausea	0.00	9.54	0.00	0.00	0.00	0.00	28.62	0.00	0.00	0.00
Oculomotor	0.00	15.16	0.00	0.00	0.00	0.00	7.58	0.00	7.58	15.16
Disorientation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.92
Total	0.00	11.22	0.00	0.00	0.00	0.00	14.96	0.00	3.74	11.22

AFTER

D	E	F	G	H	I	J	K	L	M	N
	1	2	3	4	5	6	7	8	9	10
General Discomfort		0	0	0	0	1	1	0	0	0
Fatigue		0	0	0	0	0	0	0	0	0
Headache		0	0	0	0	0	0	0	0	0
Eye Strain		0	0	0	0	0	0	0	1	0
Difficulty Focusing		0	0	0	0	0	0	0	0	0
Increased Salivation		0	0	0	0	0	0	0	1	0
Sweating		0	0	0	0	0	0	0	0	0
Nausea		0	0	0	0	1	0	0	0	0
Difficulty Concentrating		0	0	0	0	0	0	0	0	0
Fullness of Head		0	0	0	0	0	0	0	0	0
Blurred Vision		0	0	0	0	0	0	0	0	0
Dizzy(Eyes Open)		0	0	0	0	1	0	0	0	0
Dizzy(Eyes Closed)		0	0	0	0	0	0	0	0	0
Vertigo		0	0	0	0	0	0	0	0	0
Stomach Awareness		0	0	0	0	0	1	0	0	0
Burping		0	0	0	0	0	1	0	0	0
	1	2	3	4	5	6	7	8	9	10
Nausea	0.00	0.00	0.00	0.00	0.00	19.08	28.62	0.00	9.54	0.00
Oculomotor	0.00	0.00	0.00	0.00	0.00	7.58	7.58	0.00	7.58	0.00
Disorientation	0.00	0.00	0.00	0.00	0.00	27.84	0.00	0.00	0.00	0.00
Total	0.00	0.00	0.00	0.00	0.00	18.70	14.96	0.00	7.48	0.00

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