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Visualization of Animal Behaviour within the Space-Time Cube: A transformation framework to Improve Legibility

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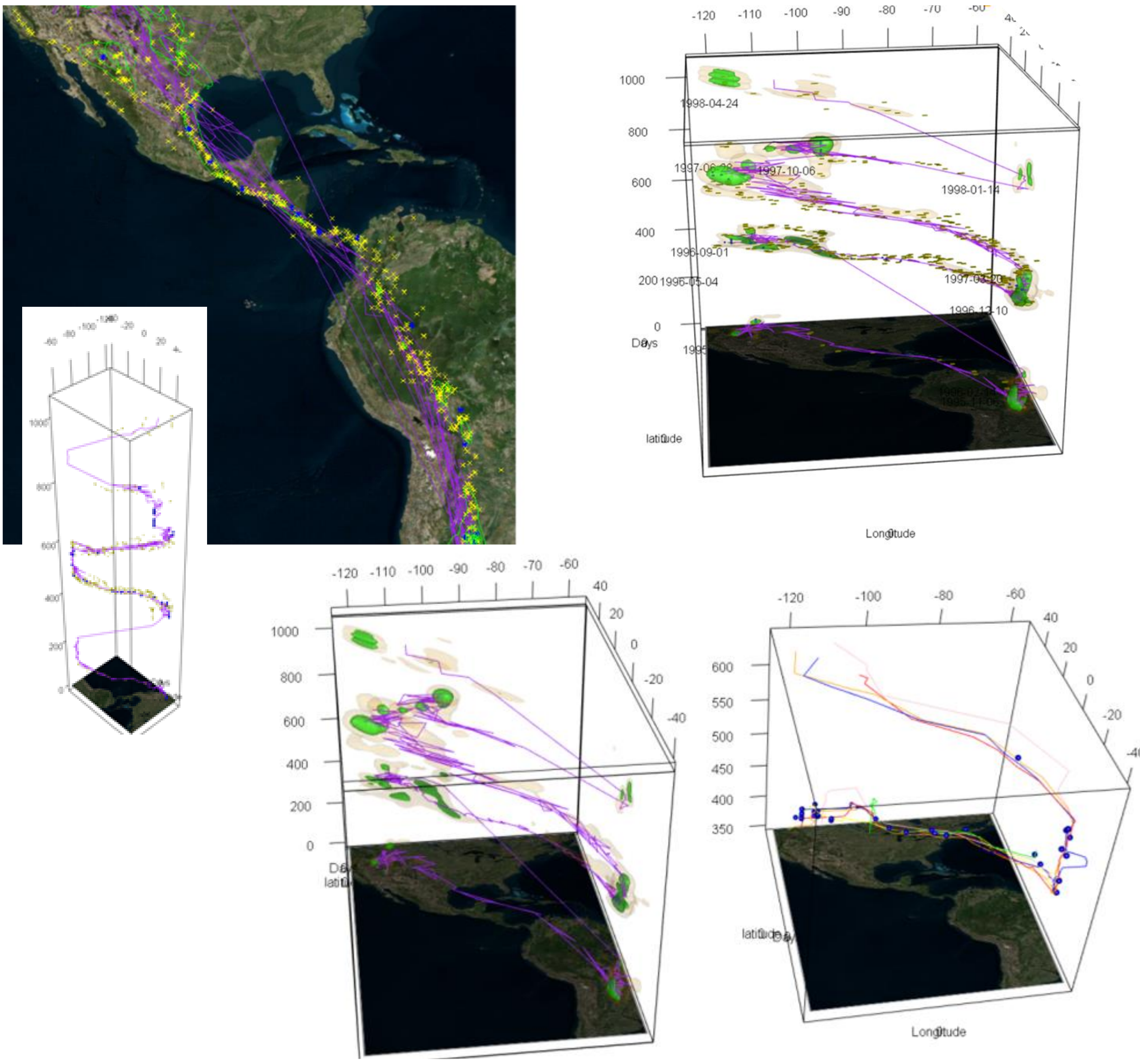

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Visualization of Animal Behaviour within the Space-Time Cube: A transformation framework to Improve Legibility

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When I searched for a thesis I definitely wanted to find something good, obviously. What that meant for me was a project that combined my backgrounds in ecology and GIS. A project where the outcome could actually hold meaning or further science. A project that I could learn from and a project that I would just generally enjoy. I like to believe I found all those things in this project looking at the Space-time Cube. It was not easy at first and as with most of my fellow students I had to stumble my way past a few obstacles initially. In the end though the process was awesome from the friends and mates in the thesis room to writing and coding I enjoyed the entire process even with the stress. In the end it all culminated in this report.

I want to finish by thanking some people who helped me get to where I am and accomplish what I have. Firstly my supervisor Ron van Lammeren, who helped me formulate my topic from scratch, acted as a great bouncing board for ideas, especially for keeping my enthusiasm going throughout my thesis and finally for helping me at the end with the final crazy push. Further I want to thank the organisation movebank for making so many datasets available to users such as me to play with. Thanks goes to all the experts and users who helped to validate my findings without you this report would well not have been valid. Final thanks goes to a few specific people all my friends in the thesis room for all the lol, Francine for the support and distractions and finally my mom and dad for the support and advice in coming back to Nederland and the WUR.

ABSTRACT

The visualization and exploratory analysis of movement data is a procedure that is occurring more and more often as GPS tracking technologies become readily available and the amount of stored movement data grows. The act of movement and the patterns therein occur throughout space and time and the Space-time Cube is one of the many exploratory data analysis techniques available to study it. It is a tool where the z axis of a three dimensional diagram is used to represent time not height. Previous cases have shown the applicability of the technique to movement data including animals. However the legibility of the movement data is often limited when visualized within the Space-time Cube. The amount of data within the cube leading to a 'clutter'' effect that makes interpretation of the information contained within movement patterns difficult. To overcome this we designed a transformative framework that guides a user through a series of steps to a transformation that will visualize a more legible representation of the data for analysis. The assumptions of the framework were supported by a thorough literature review. The transformations developed were implemented using R and with specific use of the 'rgl' package. The resulting framework and associated transformation visualizations proved that clutter within the Space-time Cube could be reduced and legibility improved by way of a transformation framework. Further the resulting framework and transformations were shown to be generally well understood and appreciated supporting further development of the technique.

Keywords:

Space-Time Cube | Visualization | Transformation Framework | Legibility | Exploratory Data Analysis | R | Symbology | Scale | Animal Movement | GPS

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EQUATIONS

ABBREVIATIONS

STC	Space-time Cube
KDE	Kernel Density Estimate
BB	Brownian Bridge
GIS	Geo Information Science
POI	Point of Interest
SR	Sectional Relevance
CVV	composite visualization view
CMV	coordinated multiple views

1. Introduction

1.1 Context

Modern GNSS (Global Navigation Satellite System) tracking technologies are more readily available than ever before (Gennady Andrienko, Andrienko, & Wrobel, 2007). A major outcome of this has been the rapid accumulation of recorded movement data (Urbano et al., 2010; Zheng, Zhang, Xie, & Ma, 2009). The possibilities of these new data sources in conjunction with increased data accessibility have led to multiple new avenues of study for both the scientific and commercial community (Cagnacci, Boitani, Powell, & Boyce, 2010). Edwards and Griffins investigated the applicability of crowd sourced movement data in support of tourism management (Edwards & Griffin, 2013). Vehicle GPS data has been used to inform the public of traffic congestion levels (de Fabritiis, Ragona, & Valenti, 2008). Research is no longer limited by data deficiency. Now the issue is the limited capability of current analysis and visualization techniques in dealing with the new information density.

Within the field of biology this increase in accessible movement data has breathed new life into the spatio-temporal aspects of movement ecology (Cagnacci et al., 2010). A new field of study developed over the last decade. The manufacture of more advanced GPS tracking tags and collars led to an inundation of geolocational animal data and associated studies (Sand, Zimmermann, Wabakken, Andrèn, & Pedersen, 2005; Votier et al., 2010). Majority of these studies focus on spatial movement aspects; home range estimation (Walter, Fischer, Baruch-Mordo, & VerCauteren, 2011), movement patterns (Ordiz, Støen, Delibes, & Swenson, 2011) or movement interactions (Masello et al., 2010). Locational studies that consider spatial movement are not a new thing with telemetry being the original data source (Craighead & Craighead, 1972), an often exhaustive and slow process. Comparatively modern GPS tracking technologies allow for reduction in the temporal sampling period (Handcock et al., 2009). Decrease in sampling period means more data recorded within a shorter timeframe, providing a better image of temporal and spatial movement.

Many methods exist to study spatio-temporal data and among them is the Space-Time Cube (here on referred to also as the STC). Formulated by Hägerstraand in 1970, the STC uses a three dimensional space to present spatio-temporal data with the third (Z) axis being used to present time instead of elevation (height) (Hägerstraand, 1970). However the increase in data has led to clutter in both the spatial and temporal dimension during visualization, including within the STC (Gennady Andrienko & Andrienko, 2011). If the issue of clutter was overcome the STC could become an important tool for the visual analysis of spatio-temporal movement data.

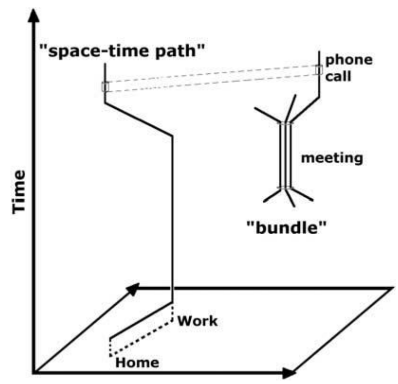

Figure 1: Space-time cube example (Vrotsou et al., 2010)

1.2 Background

The initial Space-time Cube designed by Hägerstraand in 1970 presents time as a visualized dimension. A spatial map contains the standard two dimensions; X and Y. Hägerstraand adds the Z axis to form a cube so as to visualize time in the place of height in a standard three dimensional image (Hägerstraand, 1970). In this way all instances of an activity in time can be visualized simultaneously (depending on the unit size). The principle of Hägerstraand's idea is that change in spatial location over time and the patterns within are translated in a legible manner to the user (Irma Kveladze & Kraak). However though the principle was sound, at the time that Hägerstraand released the STC the technique could only be carried out on paper. The STC required a draftsman to construct a single viewing angle due to the limitations in computation at the time (Kraak, 2003). Due to this lack of utility Hägerstraands creation was pushed to the back burner. The technique lived on in simplified forms such as the Hägerstraand scheme. But due to the time consumed when altering views Hägerstraand's cube as he imagined it could not be used (van der Knaap, 1997).

Parallel to formulation of the Space-time Cube and afterwards contemporaries of Hägerstraand further expanded upon space-time theory. There are aspects of these theories that are of note to this thesis and should be carried across when further consideration of the STC is made further on. The first is that in any evaluation of an event three elements should be considered; Space, time and context (Bracken & Webster, 1990; Langran, 1992). The purpose of recognizing these three elements is that in any space-time visualization the goal in terms of space-time should always be considered. As a set of notions this could be interpreted as the aim for which an object is visualized, the specific relevance of time to the object (in what form is time most descriptive and relevant to the object from the perspective of the user) and what perspective the user is viewing from both spatially and generally (certain scales can influence a user's perspective). Notions are based loosely on features described by Bishr (Bishr, 1998; van der Knaap, 1997; Yuan, 1994).

Since Hägerstraand's development of the STC and the growth of space-time theory the scientific community and society in general has been blessed to witness an increase in computational power and data availability (I. Kveladze, Kraak, & van Elzakker, 2013). These improvements extended across all fields including movement data. Where once the issue scientists faced was data availability, now a lack of suitable analysis techniques is the greater issue (Porter, Hanson, & Lin, 2012; Slavakis, Giannakis, & Mateos, 2014). It is like all the materials to build a house have been provided but the blueprint interpreting the one into the other is missing. With a deluge of data available and the necessary computational power needed for analysis available it is now the analytical techniques that limit research. Attempts to overcome this bottleneck by researching methods new and old are being undertaken. The effectiveness of techniques in studying movement data is also being tested (Gennady Andrienko et al., 2007) (G. Andrienko, Andrienko, Hurter, Rinzivillo, & Wrobel, 2013).

Among the old techniques being reconsidered is the Space-time Cube. Increases in computational power since the birth of Hägerstraands STC has made it into a viable analytical tool. Since realising this multiple studies have utilised the STC. Willems considered the visibility of vessel movement trajectories in Space-time cubes when compared with other visualization methods (Willems, van de Wetering, & van Wijk, 2011). Huisman Considered the applicability of the STC for use in Archaeological studies (Huisman, Santiago, Kraak, & Retsios, 2009). Coastal terrain change was visualized using the STC by Tateosian (Tateosian et al., 2014). With respect to people, Orellana used crowd sourced data to analyse visitor movement within a recreational area (D. Orellana, Bregt, Ligtenberg, & Wachowicz, 2012). Applicability of the technique to animal movement and the field of Ecology has also been researched. Demsar constructed space-time densities within a STC for the analysis of lesser black backed gulls movement data (Demsar, Buchin, van Loon, & Shamoun-Baranes, 2015). Alongside proving the applicability of the STC, other studies have gone on to check the STC's comparative effectiveness. Comparative studies have considered the effectiveness of the three dimensional STC versus standard two dimensional mapping approaches. The results show that for complex data queries an answer is easier to find within an interactive STC visualization then in standard two dimensional visualizations (Gonçalves, Afonso, & Martins, 2014; Kristensson et al., 2009; Vrotsou, Forsell, & Cooper, 2010). Yet applicability and comparative usefulness aside there is a distinct restriction to using the STC caused by cluttering (see Figure 2). Clutter's definition from a viewing perspective being a collection of objects lying about in an untidy state.

Within STC visualizations clutter occurs when the number of tracks or their length goes beyond a certain threshold (Gennady Andrienko & Andrienko, 2011). In the case of the STC that threshold is generally set using Miller's Law of 7 ± 2, recognized as the maximum number of objects a standard human can hold in their working memory (Miller, 1956). Therefore the same number of trajectories or lines is recognized as the general threshold to "clutter" (Gonçalves et al., 2014). Below this threshold a person can still visually identify separate tracks and anomalies of interest. Beyond that threshold a human working memory simply cannot keep track of old differences as well as discerning new differences (Arsalidou, Pascual-Leone, Johnson, Morris, & Taylor, 2013). An inherent trait of animal movement data is that the trajectories are long and full of variation, making them inherently prone to cluttering. Therefore when multiple animal trajectories overlay they easily become illegible. The issue has to some extent been solved, with techniques used to transform and interpret illegible data (Demsar et al., 2015) (Kraak et al., 2015). Yet a problem exists in that those techniques are not generally applied, the basic STC visualization approach to space-time data consists of plotting all geolocations, connecting the dots and forming trajectories. When those trajectories and geolocations become too numerous or complicated they are visually perceived by the human eye as what can essentially be considered three dimensional "*confetti*" and "*silly string*"

There is no pre-existing format in STC application to decide what transformation or formatting is most suitable for a specific dataset. No standardised method to decide how to best retrieve the information contained within. Techniques and transformations do exist and have been applied to both two dimensional maps and three dimensional cubes to overcome these issues to some extent. Yet they are not connected to clear scenarios of use such as in statistical analysis strategies and are spread across multiple platforms. This last point is of specific interest as it limits the growth and applicability of the STC. Kraak (2013) in his work utilises a specialised platform for visualization inaccessible to most outside the field of geovisualization. Similarly Baas (2013) in his Masters used ArcScene a program that comes with high access costs and is reliant on the parent company for further development. The formation and implementation of a framework within an accessible platform, that connects respective scenarios of movement to specific formatting techniques would increase the applicability of the Space-time Cube to all fields.

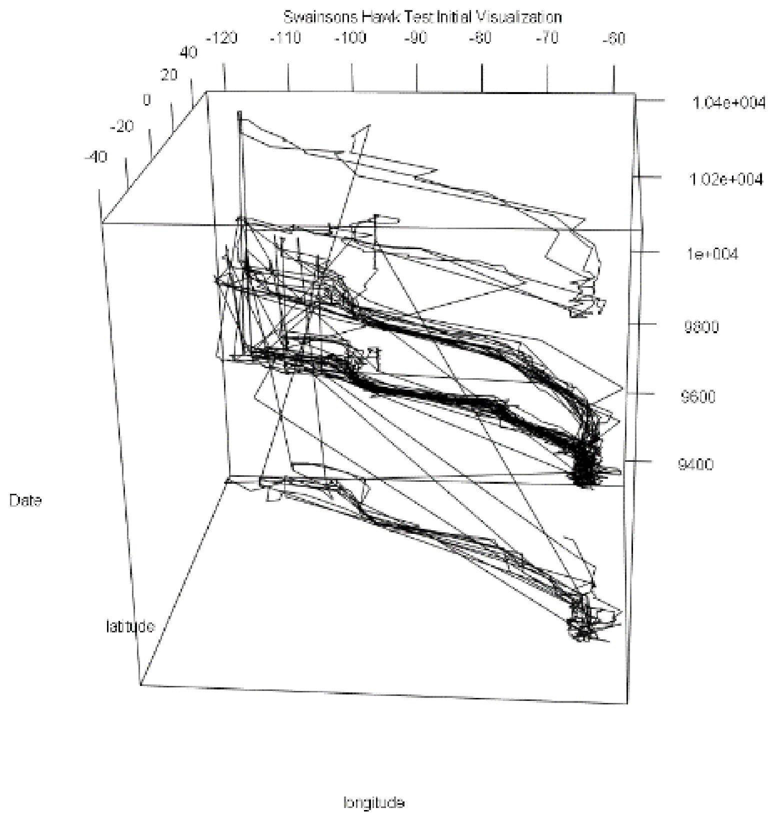

Figure 2: A Space-time Cube showing the effects of "clutter"

1.3 Research Objective and Questions

The overall objective of this thesis was *The construction of a framework of strategical transformations*[1] *for the analysis of animal movement within the Space-time Cube so as to improve analytical legibility while reducing clutter.*

The four research questions that accompany this research objective and if fulfilled should result in completion of the objective are as follows:

Research question 1:

> *For the purposes of constructing analysis strategies how is animal movement visualized, scaled and symbolised and can it be applied to the Space-time Cube ?*

- *Can basic classifications of Animal movement be organised into a form applicable to the purpose of constructing a matching grouping of Space-time Cube visualizations ?*

- *How has spatio-temporal animal movement previously been visualized, scaled and symbolised?*

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[1] **Framework of strategical transformations** – In the context of this thesis is; A structured set of strategically chosen data transformations each one aiming to best interpret and visualize a different type of space-time animal movement within the space-time cube. | **Framework** – A structural plan or basis for a project. | **Strategy** – A plan, method, or series of manoeuvres or stratagems for obtaining a specific goal or result.

Research question 2:

> *Can we aggregate current space-time cube visualization strategies into a strategical framework with matching classifications of animal movement ?*

Research question 3:

> *Is it possible to run the visualizations of this framework's transformation strategies within the open source program R ?*

Research question 4:

> *Can the value of the categorical framework and its implementation be assessed and validated thereby proving the value of the produced outcomes ?*

1.4 Reading Guide

The following is a short description and guide to the chapters found within this report

The report begins with the introduction that introduces the subject and background of the thesis and the idea being focussed on here the STC. It also further presents the research objective and related research questions. This is followed by the literature review the answer research question one. It is an in depth consideration of the material that discusses the points within the research objective and research question one. The literature review is further split into seven sections, for details read the section *approach and scope* within the review itself. The methodology follows afterwards and describes and explains the processes that were undertaken to answer research questions two through to four. Specifically this concerns the design of the framework, implantation of the transformations and the validation of both products. The results come after and describe the outcomes of the thesis following the same structure as the methodology. Finally the thesis is concluded with the Discussion. Here all the research questions are concluded and examined with respect to the limits of the outcomes, relevant comments from within the validation comparisons to other works are also made. The report finishes with recommendations for the future and a final conclusion.

2. Literature Review

2.1 Introduction

Animal movement takes place in space and time simultaneously. Such movement analysis utilises aspects from both the field of Ecology and GIS (Geographic Information Science). Originally the study of animal movement was considered a sub focus within the biological sciences. However, the arrival of new GPS technologies overturned this assumption renewing the importance of the spatial-temporal element. Spatial-temporal analysis is often completed visually and in many ways the visualization of data needed to undertake exploration can be considered a sub focus on to its own. With the growth in modern computing in recent decades' visualization as a study has grown continuously as has its capabilities.

We focus within this review on the capabilities and utility of the Space-Time Cube (STC) as a visualization tool to study animal movement data . Focussing in on its application to the study of animal behaviour. To accomplish this, we consider three separate fields within the review; Ecology representative of the behavioural aspect within animal movement, GIS representing the cartographic spatial-temporal aspect mentioned previously and Visualization the means by which analysis of the two former fields becomes possible. Each field will also be examined from the perspective of building a framework of transformations using symbology and scale. Two ideas prevalent in all three fields. By reviewing and utilising the best current practices from all three fields a path to our research objective may be found; *The construction of a framework of strategical transformations for the analysis of animal movement within the space time cube so as to improve analytical legibility while reducing clutter*.

2.1.1 Approach and Scope

The three fields of GIS, Ecology and Visualization as well as the research objective as a whole are all considered within research question one as represented by this review. Our approach is based upon making sure all the aspects are thoroughly considered. And that we specifically considered them in terms of current and past methods for the visualization of spatio-temporal animal movement. For the development of a framework of transformations focus was also placed on the theories of scale and symbology as well as the use of scale and symbology within STC related methods. The reason being that it is through the use of scale and symbology that the transformations will be constructed. Finally we consider how those techniques and concepts found could be linked to STC visualization. When we met these points the final goal was the incorporation of the discovered information into a strategical analysis framework during the second section of the project.

To fulfil all these points we had to find a suitable format for our literature review and break down the requirements of the research question into manageable parts. We considered the format of multiple published reviews, not limited to the field of GIS. The review strategy that resulted consisted of searching through multiple papers relevant to research question one on the basis of keywords and phrases. Those papers selected were then scanned for relevance and if found relevant reviewed in full. If information of great interest was found such as a concept or technique that paper was reviewed again and summarised by means of the format shown in the exemplar in appendix A[2]. Summaries of the most relevant literature pieces were made. Within the summaries the sections they relate to can be found under SR (Sectional Relevance). Their most relevant points as they relate to this project were recorded under POI's (Point of Interest). All summarised pieces are marked with a (*) in the reference list.

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[2] The complete set of 15 literature summaries can be found on a CD within the GIS department of the WUR and are retrievable upon request

So as to make the review as targeted as feasible the requirements of research question one was broken down into five parts that translated into seven sections in the literature review. The structure of the review is as follows. Five focuses preceded by an introduction and followed by a conclusion summing up the results. The results of each section are often related to the next section therefore the review is sequential. The second and third sections after the introduction are the largest and receive the most focus. We begin by considering the *Origins, Uses and Issues of the Space-Time Cube in terms of Symbology, Scale and Visualization*. The concepts of symbology and scale as they relate to this project are outlined here as well as any points of scale and symbology usage that may inform on the development of transformations. At this point in the review investigation into methods of STC validation and assessment are also undertaken. This is done so that the eventual outcomes of this project can be assessed as stipulated in research question four. Review of biological aspects of the objective begins in section three with a *consideration* of *defining and classifying Animal Movement Behaviour in a spatio-temporal context*. The last three sections are shorter, the more theoretical aspects of the review already having been covered. The fourth section focuses in on *previous visualizations of animal behaviour* keeping in mind the theories of the two previous sections. Within section five the review turns more technical as we examine *utilisable frameworks and applicable spatio-temporal transformation strategies*, from both new and previously considered works. Section six quickly covers *implementation of the STC and available platforms*. A conclusion at the end summarises the results of the review as a whole, combining all aspects.

2.2 Origins, Uses and Issues of the Space-Time Cube in terms of Symbology, Scale and Visualization

This section starts of the review proper by identifying and describing the origins of the Space-Time Cube. From there we consider the purpose of the STC and how it has been used both in the past and the present. Further we consider the theoretical ideas that support different usage examples. Specific focus is given to the comparative usefulness of the technique when matched with other techniques, the value of the technique and the issues that still exist. Issues to do with analytical legibility such as cluttering, a focus of this review. Throughout and at the end of the section we analyse how these separate aspects relate back to one of the goals of this project the development of a framework through the concepts of scale and symbology.

The Space-time Cube originates from Space-Time theory and the original idea of the Space-Time Web. Hägerstraand a social geographer of the 1970s wanted to consider regional social geography and peoples place within it from a new and novel perspective (Hägerstraand, 1970). To do this he suggested the concept of the Space-Time Web. He believed that time and space are not separate entities and that consideration of one could not occur without consideration of the other. A perspective that as of now is largely supported. This is evidenced by the current popularity of Hägerstraand's concept and the growth of time geography overall. Further the theory that space and time cannot be disconnected is a basic pillar upon which this review sits. Within his paper Hägerstraand continues by listing three movement constraints, Capability, Coupling and Authority[3]. He suggested that these three constraints should be recognized during any analyses of movement in both time and space. It may therefore be said that an STC becomes a suitable tool for exploratory data analysis once these constraints can be recognized within the cube by the user. One of Hägerstraand's concluding points regarding biology can be interpreted from this perspective. If a life path visualized within the STC can clearly visualize the above three criteria then the concept is applicable to any aspect of biology. In translation meet the criteria and a visualization of animal behaviour can be considered a success.

Yet issues of usability prevented the STC concept from becoming widely applicable for another thirty years. The physical visualization or production of STCs in the past limited usability. The requirement for a draftsman to sketch out every angle did not lend itself towards efficient exploratory data analysis (Kraak, 2003). Today with modern computational capabilities the situation has been reversed and opportunities within geovisualization and for the STC are only growing. The advance of computational power also brought to the front new possibilities and issues for big data. This accessible mix of new possibilities and investigable issues has brought forth a tide of Space-Time Cube usage, this last decade. Willems et al. considered the visibility of vessel movement trajectories in Space time cubes while comparing concurrently with other visualization methods (Willems et al., 2011) . Huisman et al. and Llobera both considered the applicability of the STC for use in Archaeological studies (Huisman et al., 2009) (Llobera, 2011). A less object orientated use was the analysis of coastal terrain using the STC by Tateosian et al. (Tateosian et al., 2014). From a human geography perspective Orellana et al. used crowd sourced data to analyse visitor movement within a recreational area (D. Orellana et al., 2012). Nakaya and Yano considered the rate of snatch and grab crime statistics in Kyoto (Nakaya & Yano, 2010). Evidence for the applicability of the STC as a visualization technique is abundant and widespread. The concepts applicability to animal movement/behaviour analysis is discussed separately within section three.

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[3] **Capability** – an individual's capability for movement within the limits of time and space | **Coupling** – limits on an individual's location within space and time due to events that require proximity to other individuals | **Authority** – locations that have limited access not due to capabilities but due to the territorial influence of other individuals. Adapted from (Hägerstraand, 1970).

The general applicability of the Space-Time Cube is proven and its original purpose according to Hägerstraand examined. Now we switch our focus too investigating the comparative usefulness of the STC, its value and what issues there still are with the technique. To undertake this task, reliable evaluation methodology is necessary. Methodology seems to be split amongst two general focuses. Comparative evaluations, generally with other 2D and 3D techniques (Gonçalves et al., 2014) (Kristensson et al., 2009) (Vrotsou et al., 2010) or evaluations from an operationalist and design perspective (Kraak, 2003; I. Kveladze et al., 2013). From the second focus the work of Kveladze is of specific interest as it is the first STC research we found with the goal of constructing a methodological framework for the purpose of Space-Time Cube evaluation and improvement. Kvelkadze takes the view that use of visualization techniques within the STC is context dependant, a point agreed upon by us. The format suggested by Kveladze is to follow a three step research framework. Where a problem is recognized, a solution formulated and the result evaluated. Each section goes into more detail in how to approach use of the STC. For example, within her Framework after identifying the problem the solution for a large part consists of considering the problem from the perspective of improving the zoom and detail. It should be noted that Kvelkadze also recognizes the issue of clutter in the same context as us (I. Kveladze et al., 2013). The result produced is evaluated by user/domain experts on the basis of having or having not achieved the end goal. She proves the utility of her framework and the value of her work as a whole by applying it to four case studies of varying difficulty and subject material. In each case she improves upon the initial STC visualization.

In comparison to Expert evaluation, that works on the basis of operational knowledge the alternate method comparative evaluation utilises multiple parties where expertise is a lesser requirement. Due to a lack of domain experts, the STC still being somewhat new and complicated the latter is generally the more popular method. Further comparative studies have a greater metric measurability. As STC visualization requires domain knowledge to perform the need to prove the value of the technique over simpler 2D techniques in exploratory data analysis may have been strong. This is evidenced by the amount of studies doing just this (Gonçalves et al., 2014) (Kristensson et al., 2009) (Vrotsou et al., 2010) (Willems et al., 2011) . The results of such studies largely concur that for simple exploratory data analysis the effectiveness of 2D visualizations is just as good or better then 3D STC visualizations of the same material. However, as the complexity of the question being investigated increases then the effectiveness of STC visualizations is generally shown to be better. The method by which questions were categorised differed slightly per study[4], but generally as the complexity and open-endedness of the question increased the value of STC investigation also improved. Some studies do disagree. Seipel investigated the influence of the strength of a 3D visualization on exploratory data analysis when compared with and against 2D visualization. The results in this case showed 2D and weak 3D visualization to be just as effective and strong 3D visualization being less so (Seipel, 2013). Based on these varying results it can be stated that there is definite value in data analysis using 3D STC visualizations. But the exact niche where it fits still has to be found. Use value has been shown to be context dependant, for simpler questions the more affordable 2D solution is often the more practical option. And for more complicated questions transformations may sometimes be required to make it effective. Vrotsou also makes mention of the issue of clutter within 3d visualization (Vrotsou et al., 2010). The value is therefore clearly context

[4] **Simple / Elementary Questions** – Questions of what, where and when often involving metric properties, situations where space and time can be considered separately | **Complex / General Questions** – Questions that linked where and when as well as how and why and often involved ordinal properties, an understanding of the datasets spatiotemporal structure is usually needed. Adapted from (Kristensson et al., 2009) (Gonçalves et al., 2014).

dependant and further evaluation and improvement will require the application of research frameworks such as that produced by Kvelkadze.

Previously the term ‘clutter’ was mentioned in connection to the work of Kvelkadze. It is a term that can be considered the flagship for issues of legibility within the whole study. It is in simplest context the problem that requires solving. We discussed previous evaluations earlier as a lead up to investigating the issues the STC faces. Among the evaluations discussed in many cases the amount of life-paths or subjects considered within the STC being evaluated was limited to less than seven. In those cases, where the threshold of seven was approached the evaluations often mentioned that the quality and ease of analysis decreased. This occurrence is what we recognize as ‘clutter’. Beyond Kvelkadze, Vrotsou et al. (Vrotsou et al., 2010) as well as Andrienko and Andrienko (Gennady Andrienko & Andrienko, 2010) use the term in reference to a build-up of life-paths within the Space-Time Cube. Based on all the references to clutter within the literature considered we view clutter from an STC standpoint to be:

“A build-up of space-time objects within a Space-time Cube during visualization of a large dataset. The resulting visualization is beyond the capabilities of a humans working memory to interpret. Leading to impaired exploratory data analysis”.

Though we find the term useful as a representative of the issues with legibility the term is not found within all papers considered, either because the amount of life-paths examined fell below the threshold or because the work simply utilised different terminology. However, we believe ‘*clutter’* to be an applicable universal term to describe the issue. For reference the threshold too effective exploratory data analysis is generally considered to be 7 ± 2 objects from the work of Miller (Miller, 1956). Our labelling here of the issue with STC visualization does not mean the scientific community has sat by idly before this. There is evidence throughout the reviewed literature of multiple transformations being suggested or applied to the STC (see section 5). The goal in each case being too improve data legibility or simply for the novelty of the approach.

Before considering what transformations were undertaken however we had to consider the why and the how of visualization transformations. The ‘Why’ was easier of the two to discover. In some form of another most of the works considered gave reference to the idea of context. Some specifically and others more indirectly in their approach. We view the application of specific inquiry to a specific problem as finding a context dependant solution. Of all the literature reviewed Puequet states it best, even being referenced in others work (Vrotsou et al., 2010). She says that *a chosen method of data representation is always linked to a specific analytical task in mind* (Peuquet, 1994). Alternately some works have produced theoretical universal transformations for visualization meant to be applicable to any dataset, however as far as we investigated none have been applied yet in practice (Frank & Timpf, 1994). We are more supportive of Peuquet’s opinion that any transformation is personalised to some extent to the context of the problem. We consider context to be the answer to the why of transformation within visualization.

The second point the ‘How’ of transformations is more complex. We consider in this section not the specific transformations performed themselves that is left to section four. Here we briefly examine the theoretical underpinnings of transformations; Scale and Symbology and to a lesser extent zoom and rendering. These are the two facets that when used in a transformation allow transformed data to carry the same or more informational content then originally. Use of certain parts of the theoretical underpinnings of these four theories allows transformations to be designed, categorised and applied. On the basis of the results of this review we formulated definitions for the four concepts of Scale, Symbology, Zoom and Rendering [5]. Definitions that place the concepts within the context of this project and the STC specifically. The best work we found with regard to these four ideas was that of Frank and Timpf (Frank & Timpf, 1994). Within their work they propose what they call an *intelligent graphical zoom* within the context of a *multi scale data structure*. Their goal does in some respects diverge from the work being considered here. For one thing they considered general cartographic visualization not the Space-Time-Cube. For another the aim of Frank and Timpf in 1994 was the construction of a generally applicable product. They succeeded in producing the theoretical product, the practical product has still not been produced and again only context specific cases have succeeded. Yet the theoretical value of their idea and the two concepts in italics above remains high. The intelligent zoom they propose is from our perspective a context dependant tool. It can be considered an amalgamation of the four factors listed above. Within the context of the STC and our study we translate the theory of their intelligent graphical zoom as such; The use of context specific 'intelligent' symbology[6] produced through transformations and rendered to the necessary 'intelligently chosen' scale level. Each such product is visualized as a step within their second theory a multi-scale data structure or MSDS. A multi-scale being a scale with multiple categorically (not continuously) organise steps or scales. MSDS being the combination of all the intelligent graphical zoom products, each product being a step on the scale. Each step selected so as to represent the total amount of information within the dataset when the whole scale is considered. The total product should therefore present the information in the easiest and most effective manner possible. Though not to the extent of Frank and Timpf's theory the idea has been applied practically within many works and we support its theoretical worth.

We aim therefore for a multi scale data visualization framework that aims to meet Hägerstraand's original three constraints as well as the questions proposed by Kristensson (2009) and Gonçalves (2014) and the decisions discussed by Orellana & Renso (2010). Thereby dealing with the issues such as 'clutter', identified throughout the literature. We do this by identifying the appropriate zoom levels on which to focus within GIS and ecological scales, whatever those may be. The same goes for appropriate symbology. With this it should be feasible to construct a focussed STC for a context specific case such as animal movement.

[5] **Symbology** – The transformation of one graphical representation of a dataset into another for ease of visualization and interpretation of the original info does not specifically have to be a geo-dataset | **Scale** – Total amount of levels within a visualization and the amount of progression between them with regards to the presentation of info (a graduated series) | **Zoom** – Sub category related to scale, the depth of information presented per level and the ease of change between levels within a scaled visualization | **Rendering** – Sub category related to both symbology and scale, amount of detail presented per visualization level. Adapted from standard dictionary definitions and (Frank & Timpf, 1994).

[6] **Intelligent symbology** – A complicated way of saying smart use of symbology.

2.3 Definition and Classification of Spatio-temporal Animal Movement Behaviour

Within this section our aim is to investigate and consider the definition of animal behaviour and the different classifications or categories of scales within animal behaviour. Ultimately we hope to do this all in terms of a spatio-temporal context. By reclassifying these definitions from a spatio-temporal perspective it will allow for the identification of specific animal behaviour categories. These categories or patterns once identified may then be classified and represented more legibly within the STC. Achieved via transformations using specific symbology and scale. The final goal being the development of a context specific multi scale data visualization framework such as that examined in section two. One specifically focused on visualizing spatio-temporal animal movement behaviour.

With any investigation of a theory one should start with the basic concept and accrue from there. In this case that basic concept can be found at the end of the section title and accrued by moving left. Animal Behaviour the core of this theory is funnily enough defined as being the 'study' of the behaviour of animals not the act itself. The actual act of an animal's behaviour is considered; *motion of an animal, internal or external in response to their internal or external environments*. This definition approaches the theory where our interests lie, yet the specifics of the spatio-temporal context is still lacking. For instance, from the perspective of the STC one could theoretically visualize the movements within internal organs over time. Li et al. provides evidence for the feasibility of such a study when they investigated eye movement data within the STC (Li, Çöltekin, & Kraak, 2010). Yet however feasible, for now a physiological study such as this lies outside the scope of this study. The main reason for this is that our study is based around the use of GPS technology for data retrieval. Accuracy in this case does not go beyond the meter level in general and definitely does not approach internal measurement. We can therefore say that the spatial aspect of animal behaviour should be considered to be any action taken that is visible and measurable by GPS technology. Similarly, the temporal aspect of animal behaviour is determined by both the total period of GPS data retrieval and the interval between data retrievals. In most cases this temporal limit can extend from the second scale level upwards. So the theory of Spatio-Temporal Animal Behaviour classified from a simple mechanistic standpoint can be considered any *action taken by an animal that has been measured with a specific accuracy within both space and time*.

Yet, a general mechanistic classification is not enough. This study aims to produce a STC framework utilisable by ecologists. Specifically, those in the fields of resource and movement Ecology that consider data at the spatio-temporal level we are working with. Selection of the groups previously mentioned as users is based on and supported by previous thesis work undertaken in the same field by Baas (Baas, 2013). He investigated the applicability of the STC to animal behaviour analysis. The results from his work showed that there was potential for the application of the STC to resource ecology. Issues were found with the legibility and ease of use of his product that brought the applicability into question. It is partly for this reason and the issue of analytical legibility previously mentioned in section two that we believe a more context dependant categorical classification of spatio-temporal animal behaviour is required. A theoretical concept that links the Geo-information based STC context with that of the user based resource and movement ecology contexts. We achieve this by breaking down animal behaviour into its spatial and temporal parts and considering both from a GIS and ecological perspective simultaneously.

We begin with the subject. This is where the focus of any STC visualization should always lie. In the case of animal behaviour, the subject unit of interest is simply the animal itself. Within Ecology these subjects of interest can be split into three general units; the Individual, the Population and the Community [7]. The ecosystem is not included as it is the community in action, a process in time and currently too complicated for the STC. General behavioural characteristics can be applied or extrapolated to all three levels (Cagnacci et al., 2010; Dasmann & Taber, 1956). This means a population or community can be studied as having a generalized behavioural pattern. It is here that it becomes important to mention the use of symbology for a moment. For it is by representing the generalized behaviour pattern of multiple individuals, in GIS terms multiple data points as a single data point that symbology is being applied. The original data being interpreted as a single aggregated symbolic individual. Admittedly the generalized behavioural pattern applied is not the true pattern except for hive species such as ants or bees, it is however a useful compromise for analysis. Yet the ecological unit of interest alone cannot provide a functional framework. This is due to each animal unit occurring at multiple different geo spatial and temporal scales, dependant on the subject organism. The species of the animal itself is also a concern for many reasons, but since there are so many each with its own unique traits and as there exists an organised taxonomy it can remain a unique variable. Thus beyond the species and the unit of interest we need to consider scale both spatially and temporally so as to be able to produce a functional contextual framework. We originally derived in the section two that in its simplest form scale is *a graduated series*. From there we developed our own interpretation of scale within the context of STC visualization.

Total amount of levels within a visualization and the amount of progression between them with regards to the presentation of info

The core point here is the presentation of info in levels. Therefore, implementing the STC scale requires recognizing what to place on each level and the progression between. Hence an understanding of the differing perspectives on spatial and temporal scale is required.

We examine the spatial scale first. Cartographically spatial scale is seen as *the ratio of the unit distance on the map vs. that on the ground* (Andrew K. Skidmore, 2007). It is an exact measure not applicable to context dependant ecology. Attempts have been made to bridge the gap (Andrew K. Skidmore, 2007). Yet these attempts are much too rigid.

Table 1: Comparative definition of cartographic and ecological scale (Estes & Mooneyhan, 1994)

Cartographic scale	Ecological scale
1:10,000 or larger	Site
1:50,000 to 1:250,000	Regional
1:250,000 to 1:1,000,000	Continental
1:1,000,000 or smaller	Global

In the case of the use of Site from Estes and Mooneyham it is also too unclear. A garden can be considered a site for a population of ants. Yet the Pacific Ocean can also be considered a site for a population of migratory birds. Skidmore and Ferwerda believed that developing an ecological scale that matched the geographical scale was possible. On this we would agree as long as the scale produced remains mutable. The relation between the varied real world size of an individual, population or community and the graphical cartographic representation is not simple therefore the scale cannot be static. The scale of Cartography is rigid and rightly so. Pure cartographical mapping for navigational purposes is a precise act. However modern Geo-information has a wider purpose and has seen that

[7] **Population** – A group of organisms of the same species that coexist together within the same spatial location. | **Community** – A group of different species populations that coexist within the same spatial location. | Ecosystem

rigidness decrease. Due largely to the capability to produce a variety of maps more quickly and with greater versatility. Logically the standard assumptions of rigid scales have also become challenged, including within this study. A spatial scale that links between both the GIS and ecological world needs to take into account the animal unit, the species mobility and select a cartographic scale for reference based on the outcome.

Turning now to perspectives on temporal scale. As in the case of the ecological spatial scale the temporal ecological scale follows much the same format. Where empirically the temporal scale can simply be broken down into seconds, minutes, hours, days etc. The ecological variation is as vague as its spatial counterpart and dependant on the activity period of the organism being studied. Taken from a chapter of *Resource Ecology 23rd edition* the main temporal levels according to Owen-Smith are; *Yearly, Seasonally, Daily* and *Day-Night* (Owen-Smith, 2007). To this list we would also add *Tidal (*phases between tides) and *Phenological* (period spent in a certain physical form) on the basis of Owen-Smiths own criteria. Owen-Smith selected these levels or scales on the basis that they all present variety. Specifically, if a scale presented a variation of animal behaviour patterns not previously found. The chapter focuses largely on the foraging activity of animals, documented as a foraging spell. In this way the categories or levels he comes up with are highly applicable for behavioural study of GPS data. Due to the mechanistic spatial scales of the GPS data we are focusing on matching well with the temporal scales foraging occurs at. It should also be noted that hourly activity was not mentioned in the list produced by Owen-Smith. The overall discussion of his text however suggests that hourly activity is included within the other categories as a subunit. It is assumed that as a standalone unit of measure it will not present behavioural patterns of interest. A conclusion regarding a linked temporal scale can be made based on the discussion of Owen-Smith and the previously identified factors influencing spatial scales. The temporal scale much as the spatial scale can be considered a product of multiple factors. In this case the animal unit considered, the organism's life history and specifically how that translates into their active period. Where it differs specifically from the spatial scale is that its upper and lower limit are also influenced by the set period and intervals of the chosen data collection mechanism. Further within GIS the temporal aspect was never as metrically rigid as its spatial counterpart making adjustments much easier.

Both the spatial and temporal aspects of scale have been considered now from a GIS and ecological perspective. Thus our classification and categorisation of spatio-temporal animal behaviour begins to take shape. There is one last facet however that requires consideration to bring it all together. Interpretation of the behavioural patterns themselves, an aspect that cannot be overlooked. For this we turn to the ontology (philosophical framework of being) created by Orellana and Renso for studying human behaviour and applied within the STC (D. Orellana et al., 2012; Daniel Orellana & Renso, 2010). The paper produced details the assembly of an ontology for the recognition of pedestrian behaviour. Though a slightly different focus humans are still animals and in many cases the behavioural patterns of humans when visualized can be considered to be quite animalistic. A person moves to forage (work) and interact just as any other animal. It is for this reason as well as the sound strategy Orellana and Renso followed in their work that we believe their ontology to be highly applicable to this project.

Their Ontology relies on the assumed truth of a single backing concept; '*movement is not behaviour but patterns are'*(Daniel Orellana & Renso, 2010). Based on this assumption they categorise the main types of interaction they recognise. Interactions in their eyes acting as the bridge between patterns and behaviour. Selecting interactions on the basis of multiple factors the most interesting and relevant of which is the three level decision making hierarchy originally adapted from Hoogendoorn Bovy and Daamen (Daamen, Bovy, & Hoogendoorn, 2002) by Orellana & Renso (2010). Those three levels are

Strategic, Tactical and Operational [8]. Though constructed for the analysis of human behaviour with a little latitude they are applicable to general animal behaviour. The long term migration of flocks and herds, the stocking up of food or fat for winter both can be considered a strategic decision undertaken by animals. Seeking cover in the rain or avoiding a flooded route a tactical decision. The simple act of eating grass or running exemplifies an operational decision. Using the three level Hierarchical decision making concept among others Orellana and Renso developed three categories of interaction; Pair-wise, Environmental and Collective [9]. These interactions form the basis of their ontology. They showed that using this ontology the identification of pedestrian behaviour is feasible. We believe that by holding onto their ontology and viewing even the environment as a player within the STC improved analysis and recognition of behavioural patterns may be feasible. The visualization of those behavioural patterns may once again require transformation of the behavioural pattern as denoted by the data into the appropriate symbology for representation, as with the units considered earlier (individual, population and community). Now from the outside one could say that we digress at this point, the focus of this study being the improvement of visualizing animal behaviour for analysis not the act of analyses itself. We would argue that visualization for the purpose of investigation requires understanding the methods and aims of the investigators.

With all the aspects that make up spatio-temporal animal behaviour now recognized from a GIS and ecological perspective an idea of what the theory really is and how it can or cannot be classified begins to take shape. That understanding is furthered by understanding the way behavioural movement data may be investigated. The result of investigating and discussing these factors leads to one clear conclusion. As of yet there is no overarching definition or classification for spatio-temporal animal behaviour. We are however able to propose our own working definition on the basis of this review:

'An *action taken by an animal that results in a pattern across both space and time simultaneously, given a certain extent in space and time'*

In its simplest form the classification of Spatio-temporal animal behaviour would be as above. Yet it misses the STC perspective that is of such relevance to this project. With the specific perspective of visualization within the STC included both the geo and ecological perspectives have to be taken into account as well as GPS capabilities, the definition alters as such:

'An *action taken by an animal that results in a pattern across both space and time simultaneously, given a certain extent in space and time. Measured at the necessary spatial and temporal resolution for recognition of the pattern and visualized at the most appropriate scale for identification and analysis.*'

With a working definition formulated the classification of spatiotemporal animal behaviour is the visible remaining issue. Our examination of the literature revealed that there is no generally accepted categorisation of space or time between GIS and ecology, let alone for spatio-temporal animal behaviour. The appropriate classification in each case is context dependant and built of a combination of the earlier discussed factors. This is again due to context a returning theme within this review. It seems that appropriate user focussed visualization requires optimising to the subject context. We conclude that a classification of an animals spatio-temporal animal behaviour would consist of a loosely defined group of

[8] **Strategical decisions** – Decisions regarding destinations and future aims / activities (future planning / forethought). | **Tactical decisions** – choosing what route to follow that day and response to unexpected events. | **Operational decisions** – choosing to take the next step or bite, intuitive motor control actions. Generalised here to all animals and adapted from (Daniel Orellana & Renso, 2010).

[9] **Pair-wise Interactions** – Individual-Individual. | **Environmental interactions** – Individual-Environment. | **Collective Interactions** – Multiple Individuals. Direct from (Daniel Orellana & Renso, 2010).

interlocking attributes that interact to suggest appropriate scale and symbology to transform the data in and on to for visualization and analysis of the subject.

Table 2: Interacting factors that may make up an animal behaviour classification

Eco - Spatial	**Eco - Temporal**	**Subject Unit**	**Species Info**	**Cartographic**
Site/location	Daily	Individual	Mobility	1:10,000 +
Regional	Day-Night	Population	Life History Periods	1:50,000 to 1:250,000
Continental	Seasonal	Community		1:250,000 to 1:1,000,000
Global	Yearly			1:1,000,000 -

2.4 Previous Visualization of Animal Behaviour with Focus on Space-Time Cube Usage

With the Space-Time Cube examined and Spatio-Temporal Animal Behaviour defined and to an extent classified in the previous sections we can now consider the visualization of Animal Behaviour. How it has occurred previously and how those attempts sit in terms of the theoretical constructs related to scale and symbology we have examined and produced. This section examines some of the visualization methods previously used in the exploratory data analysis of animal behaviour focusing in on those methods and techniques that were visual and utilised the STC.

Of the methods used the STC is not prominent in the least. Three dimensional use examples are extremely limited in general. In section two we mentioned the work of Baas that tested the applicability of the STC to the study of animal behaviour (Baas, 2013). The review undertaken a s a part of that project found no evidence of previous application of the STC to animal behaviour. Three years on and our own review has found three use examples within the literature (Hengl, van Loon, Shamoun-Baranes, & Bouten) (Shamoun-Baranes et al., 2012) (Demsar et al., 2015). All three examples analysed black-backed gulls and are related, the outputs of a multistep project. The presence of limited usage examples for the STC simply adds value to this project. This is for two reasons, the first is that the there are some works present that saw value in the STC and secondly it means there is work to be done in the field so as to improve it. The paper regarding the workshop of Shamoun-Baranes et al. (Shamoun-Baranes et al., 2012) supports this same theory. Specifically, they mention the lack of available accessible frameworks for construction of the STC. We would further say that is the reason for the lack of interest among users (ecologists). Ecologists are not domain experts in visualization. The remaining theoretical considerations made throughout the paper are also of interest as they largely mirror those made here focusing on the concepts of scale and symbology, space and time etc. Though not conclusive it favours the direction this review takes.

The STC users interested in animal behaviour are ecologists often lacking in the expertise necessary for geovisualization. Two dimensional visualization using static maps is comparatively easier and is growing into a standard tool for visual exploratory data analysis (Lohmann, Lohmann, Ehrhart, Bagley, & Swing, 2004) (Cagnacci et al., 2010) (Bartumeus, da Luz, Viswanathan, & Catalan, 2005). Our review suggests that though the largest proportion of ecological analyses still relies on statistical tools for data exploration visual analysis is a valued and growing field. One specific use example occurs in a home range study within Ecology. This is interesting to this review at multiple levels due to the changes to symbology involved. Within the earlier section we briefly covered how interpretation of animal movement patterns may require representing them using the appropriate symbology, here we find an actual use example. movement data being represented using polygons instead of lines or points. Further home ranges are of interest themselves their generally larger spatial scales in most cases lends itself to the mechanistic capabilities of GPS technologies. An appropriate example of this within the field of time geography is the work of Long et al. (Long & Nelson, 2012). Moving on to another case of 2D visual exploratory data analysis, David Haberkorn in his thesis investigated the spatio-temporal behavioural patterns of brown bears. More importantly he increased the efficiency of analysis by using applied symbology to identify and clearly mark possible interactions (Haberkorn, 2011). His work is further supported by the follow up project looking into brown bear home ranges (Kooij, 2015) that used symbology through polygons to represent overlapping home ranges.

Still the majority of animal behaviour visualizations found have been two dimensional, STC visualization being 2D plus at a minimum. The amount of STC visualizations in the literature for animal behaviour extremely limited. The preference among ecologists for exploratory analysis of animal movement data still remains focused around statistical tools. Yet the few forays that have occurred all agree that the technique is both applicable to the field and difficult in its application. It is of interest to note that outside of application to animal behaviour the STC is seen much more within scientific literature. Why does the first situation differ from the other, it may be that domain experts are the ones constructing and using the STC in other situations. Therefore, if the usability and understanding issue of the STC can be improved, in a way making domain experts out of ecological users, the field can be greatly improved, seeing much greater use.

2.5 Visualization Frameworks and Applicable Spatio-Temporal Transformation Strategies

We have now seen what methods have been used to visualize animal behaviour previously. Combining this knowledge with the STC and the factors that govern classification of spatio-temporal animal behaviour in a framework for visualization and analysis should result in a utilisable tool for analysis. Yet what is the value of it and what is required for such a framework and how can it be constructed. Further what transformations are applicable to which situations. It is the reasoning behind these queries we will be discussing here. The goal of this section being understanding the method behind the construction of frameworks and identifying the transformation to use within while proving the value of utilising our own eventual framework.

Throughout this review we investigated in depth literature pieces containing points of interest. Many of those are referenced in earlier sections and their relevance returns again in this one. In section two mention was made of investigative frameworks and data structures and it is with this we shall start the discussion here. For clear and simplified analysis there is nothing more valuable than the structure or framework that can act as a guide. Though stated informally the truth remains that a framework provides clarity and speeds up data exploration as well as making it more accessible to inexperienced users. Evidence for the first points can be found in the both the works of Andrienko and Andrienko (Gennady Andrienko et al., 2007) and Kveladze (Irma Kveladze & Kraak, 2012). Evidence for the increased user accessibility that a framework can provide is evident if frameworks are seen as an object that aids usage such as structures or instructions. Evidence can be seen in the focussed design of webapps for older users (Hawthorn, 2002) or in the use of user based design to improve the game experience of inexperienced gamers(Desurvire & Wiberg, 2010).

With the value of a design framework proven we consider the construction of one. For this we focus on the work of Kveladze and Frank and Timpf (I. Kveladze et al., 2013) (Frank & Timpf, 1994). Kveladze aimed to improve STC visualization through her project by utilising a three step system *of identifying the problem*, *formulating a solution* and *evaluating the result*. She focuses largely on identifying the context of a problem and formulating a conceptual design. From there she develops it into a formal design and implements a solution using usability engineering. Finally she evaluates the result through applied use of domain experts in an in situ usability analysis (within a laboratory direct environment). The value of her method is proven in results and we have attempted to apply it to this study. Within the context of this study the review can be seen as an investigation into the knowledge of domain experts. Each previous section has built upon identifying the problem with this section being the first step in the formulation of a solution.

Refocussing on the theoretical queries of this section the answer to what is required to construct a theoretical framework can also be found within the work of Kveladze as well as Frank and Timpf. Though the second study focussed on the creation of a multi scale data structure the underpinnings are the same in both cases, what is required is domain knowledge and context. Even the ontology of Orellana could not be constructed without understanding the context of movement itself, if at a more metaphysical level (Daniel Orellana & Renso, 2010). Domain knowledge applied to a contextually focussed problem is needed to create a solution. With the requirements for the construction of a framework recognized what is left is the actual construction. The solution is simple and in this case can be clearly found in the work of Frank and Timpf. We believe a framework for analysis just like a multi scale data structure must be clear, concise and made up of a step wise structure. With the construction and format of a framework recognized we now turn inward to its content. In this case *visualization within the STC for analysis of animal behaviour while improving legibility and reducing clutter*. Throughout this review we have considered all aspects of this statement and with the results of our discussion we can identify what transformations may be applicable to this situation, this context.

With the many transformations possible and the multitude of factors related to animal behaviour upon which a transformation may be based a point of focus is required so as to structure this subsection. We selected the animal unit from section three for its simplicity and the clear difference between each level. We begin with the individual. In this case the selection of interactions from Orellana (2010) provides the best reference on which to base the need for a transformation. In all the interactions categories a single or two individual life paths is all that is visualized. The third category collective interactions are the exception; we assume such interactions are generally more relevant to population unit level movements. As only two life paths may generally be visualized the issue of clutter is not present and therefore transformation to reduce it is not necessary. However, legibility can still be increased. Interaction according to Orellana is the bridge between patterns and behaviour (Daniel Orellana & Renso, 2010), therefore improving identification of such improves legibility. The thesis work of (Haberkorn, 2011) though not specifically using the STC uses simple symbology to clearly identify interaction types. We consider the symbology used within his work an applicable transformation for improving the analysis of individuals.

Moving to unit level: population we return to Orellana's collective interaction category (D. Orellana et al., 2012). At this point clutter can become an issue to legibility. The space time bundle is considered a type of feature within space time theory. By applying this feature to the population unit as a whole clutter can be reduced and more individual life paths may be visualized within the STC. This can be achieved by aggregating all the individual life paths into a single average population life path. Suggestions for variations on this same idea can be found within the works of (Gennady Andrienko & Andrienko, 2011; Shamoun-Baranes et al., 2012; Vrotsou et al., 2010). The theory behind applying individual behaviour to a population was examined in section three and it is an applicable technique. As long as it is always being recognized that a generalised view of behaviour is being viewed the transformation is applicable. Further the symbology used is simple multiple lines being represented by one, multiple points being represented by one. This way a single life path can symbolise the movements of a population.

The final unit of interest the community undoubtedly faces issues of clutter. If each individual were visualized the STC would fill up completely becoming illegible. In this case visualizing multiple population life paths as suggested before can be considered one solution. However, in many cases the interest at the community level for ecologists differs from that at the population level. Interactions can switch from direct contact to territorial. Though the former is also of interest information on the latter is also necessary. Yet population life paths result in that information being lost. As a solution we suggest using the transformation from Nakaya and Yose (Nakaya & Yano, 2010). By visualizing populations within a community as three dimensional kernel density estimations of home range new analytical information becomes available. Further clutter is once again reduced and the overlaps in territory as well as their locational change in time become clearly visible. In this way a three dimensional polygon symbolises a population in place of a single or multiple life paths or points. And multiple populations together can then represent a community It is again the reinterpretation of a dataset so as to clarify a movement pattern using applied symbology through a transformation.

We consider the above three symbology transformations (point to line, multiple point sources to line and point to area) the most pertinent to increasing legibility in animal behaviour analysis. Yet transformations using symbology are not enough. Transformations that focus more specifically on the scale of the subject are also useful. From the spatial aspect it is quite simple and set as the mobility of the species as mentioned in section three selects the spatial scale. However, mobility is not always the same within a species life history. In the case of migrating species, when on the move and when at breeding locations they can be functioning at considerably different spatial scales. Therefore, restricting or expanding the scale by focussing in on those times may increase legibility. Transformations for the temporal scale are more categorical and possibly more revealing. The standard scale of the STC is hourly or daily. Yet by changing the period of the scale to seasonally or otherwise new patterns may become clear during analysis. This is a method whose technical aspects have previously been tested by Andrienko and Andrienko within the Geospatial Visual Analytics toolkit (Gennady Andrienko & Andrienko, 2011). Various patterns become visible through their use of the technique.

Transformations have been assigned to every aspect of GIS and Ecology we have considered throughout this review and evidence as to their applicability in previous studies provided. With this if the chosen transformations using appropriate scale and symbology are placed in a clear framework following the design stratagem utilised by Kveladze (2013) as closely as possible a user friendly STC application for analysis may just be achieved.

2.6 Implementation of the Space-Time Cube, Platform Selection

For the last section we briefly consider how the framework of strategic transformations we have developed may be implemented. For this we need to select a platform, a program to use. We approach this by considering platforms previously used to implement the STC, the needs of the users and the possible future growth of the platform.

A selection of the platforms previously used to visualize the STC can be found among the works of Kveladze and in Bach et al. (I. Kveladze et al., 2013) (Bach, Dragicevic, Archambault, Hurter, & Carpendale, 2014). The first example from Kveladze was originally developed by Kraak over time and is a product of the University of Twente in the Netherlands (Kraak, 2003). Most of the examples from Bach et al. are the same, consisting of private software programs developed in house. These programs range from ESRI ArcSene to CommonGIS, GeoTime and Tardis. All can be considered effective visualizers yet they all lack accessibility and mutability. Our target users for this project include ecologists, who all have the option to use easily accessible Statistical analysis on available programming such as SPSS and R. Why should they spend money and time on a new program that requires a new training phase. Further much of the software of these programs is not easily changeable, if one wanted to change the presentation variables. We therefore suggest using R[10], a program known to both ecologists and GIS experts within the academic field. It has the capability to produce space-time cubes through packages such as Zoom, SpatialEPI and Ks. Further it has the potential to grow beyond the limits of this thesis as an open source program accessible to all. This means that therefore any code produced through this thesis is accessible and mutable in the future.

[10] https://www.r-project.org/

2.7 Conclusion

The visualization of animal behaviour by way of the space time cube, utilising applied scale and symbology to formulate transformations and improve legibility. Investigating each aspect of this statement through literature was the goal of this piece. We have achieved this here through 6 different sections. We began with the subject itself the STC and identified that Hägerstraand recognized that if the three criteria he placed can be identified then the visualization of biology and therefore animal behaviour is feasible. Further the prevalence of the term 'clutter' as a major problem of legibility was identified among the literature. Finally, a concept that was first recognized for its importance in section one and can be found throughout the review afterwards is that of context. The importance of context when aiming to visualize an object for user analysis is undoubtedly high. Understanding the importance of the concept of context, in that if transformations that make the context of the subject apparent are utilised in the STC then clutter will be reduced. In section two we discussed and discovered the context by which the differing fields of GIS and Ecology view scale in terms of spatio-temporal animal behaviour. By defining the concepts in terms of the respective fields and by identifying the varying attributes that may influence interpretation and visualization of animal behaviour we gain context. Context that may help identify Hägerstraand's three criteria, the decision making levels and interaction types from Orellana and Renso. With the theoretical base work done we switched focus to checking what visualization of animal behaviour had occurred previously. Through this we identified the limited work that has been done previously and confirmed the value of undertaking this work. Finally, we considered how theoretical concepts had been applied within a framework previously. Continuing by identifying what symbolic and scale based transformations could best be applied to the data so as to improve legibility and create context. We finished by quickly reviewing platforms for implementation and provided evidence as to why we chose R as our platform. This conclusion summarises the points of this literature review and can be read as a guide as to how we investigated the theoretical aspects of this thesis and the previous examples of work that lead to the conclusions we made and the definitions we created.

3. Methodology

Our Methodology consisted of utilising the outcomes of the literature review to produce a framework of transformations (RQ2), implement the transformations of that framework within the platform R(RQ3) and validate the outcomes of both framework and implementation (RQ4)

3.1 Strategical Framework

The goal of research question two was to *aggregate current space-time cube visualization strategies into a strategical framework with matching classifications of animal movement*. Translated this consisted of building a guiding framework in the form of a diagram. Our method consisted of first coming to understand the requirements of the diagram.

First requirement: *the general purpose of the diagram has to be to guide a user through the steps needed to visualize animal movement within the STC.*

Second requirement: *the produced visualization needs to show the most legible and representative interpretation of the animals movement patterns as feasible*.

The best way to meet the first requirement was to make the guide as simple as possible. Initially guiding the user in identifying the animal's traits thereby identifying the appropriate *classification of animal movement*. Afterwards guiding them to an appropriate STC visualization strategy or transformation.

To meet the second requirement consisted of choosing the most appropriate transformation strategy for a given type of animal movement representation. The strategy that will transform the data structure into the format that best describes the animals movement. To do this all the attributes discussed within the literature review (as seen in table two[11]) needed to be included as options. With each linked to a subject trait within the framework. We categorised the attributes into three types. The unit the animal was being considered in, The spatial context and the temporal context. Within the setting of the STC the three types of attributes can be seen as representing the three types of transformation options.

Our reason for interpreting the attributes above as transformation options is based on our understanding of the concepts discussed in the literature review. Hägerstraand listed three **movement constraints** in his 1970 paper[12]. Stating that they should be identifiable within any suitable analysis. We assume that the method to fulfil this condition is to build the most representative STC visualization possible. We hypothesize that the way to do that is to transform the data on basis of the identified attributes.

Our understanding of the **question types** concept discussed by Kristensson (2009) and Gonçalves (2014) and the **decision types** concept discussed by Orellana & Renso (2010) follows the same line. Thus we propose that by using scale and symbology to transform the original data in the directions suggested by the attributes we should achieve a more legible and representative space-time cube. *Spatial and temporal transformations should consist of transforming the data onto the correct scale. Unit transformations should consists of representing the data with the most suitable symbology for that unit.* By following this hypothesis we linked the most appropriate STC visualization strategies to animal

[11] Page (16)
[12] see appendix B for details

movement types as represented by traits. The outcome a diagram[13] that presents a strategical framework of appropriate transformations.

3.2 Implementation

With the framework built and the transformations selected we then investigated and constructed those transformations using the open source program R. Specifically constructed and ran the visualizations (transformations) suggested within the framework. It should be clarified that in this scenario a transformation is a scale and symbology based transformation of the movement data into a format for visualization. The constructed transformations the visible outcome of which are the visualizations should help to overcome issues of legibility.

Our approach consisted of investigating the transformations. Each transformation being an outcome of the strategical framework followed by construction of a subsequent function. However we found that with regards to R it was best to treat this as an ongoing process. R's open source nature and multitude of packages means that during the construction of one function (transformation) information over another may be found. Investigation and construction consequently mixed together throughout the process. Still we were able to break down our approach pre implementation into five objectives:

1. Pre-processing, general utility and usability
2. Construction of a legible empty Space-time cube template (axes, labels, title, subtitle, appropriate colours and a base map)
3. Construction of identifiable Individual life-time paths / tracks and interactions
4. Construction of a population average life-time path/track and outliers
5. Construction of 3d polygon home ranges

The first objective is connected to the goal of improving overall legibility and use. All the subsequent objectives are connected to a specific transformation outcome of the strategical framework. Objective two aims to visualize the spatial and temporal attribute transformations. Objectives three through to five aim to visualize all three unit transformations suggested by the framework.

What follows next is a description of how the objectives were approached and the steps involved. Each section is accompanied by a diagram showing the functions made for that objective (blue box) and what that function needed to achieve (green box). This report does not go into detail with regards to code or function specifics. Focus is placed on the theory behind each step and the functionality or output that step added or produced. A full description of each function can be found in the appendix[14] . Figure 20 in appendix C also provides a visual of how all the functions and scripts written link together as well as the packages used[15]. All code is available from the online repository *GitHub*[16].

3.2.1 Pre-processing general utility and usability

Pre-processing consisted of three main steps and made use of multiple packages. The first functions purpose was to transform a CSV file (targeted at movebank files) into a formatted dataframe containing only the needed columns. The goal to produce a dataframe formatted into a format accepted as input by

[13] Diagrams were produced using https://www.draw.io/
[14] See Appendix C Table 5
[15] See Appendix C
[16] https://github.com/roeldk14/ThesisSpaceTimeCubeAnimalVisualization.git

all subsequent functions. The second pre-processing step consisted of allowing for sub setting of the data based on time period. The third pre-processing step adds UTM coordinates to the dataframe.

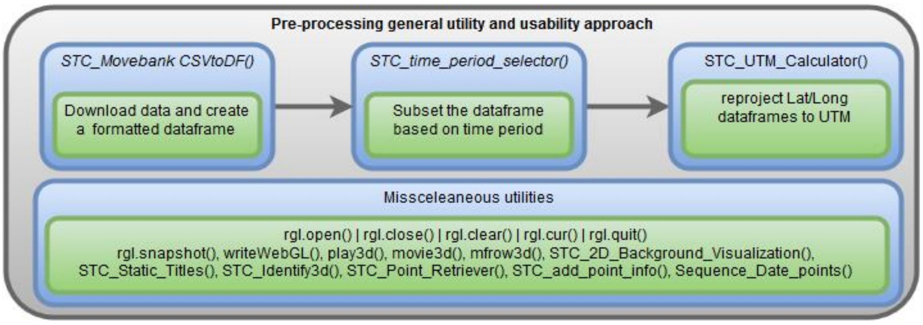

Figure 3: Pre-processing general utility and usability approach

Beyond pre-processing functionality our goal throughout the implementation consisted of providing more tools to the user and improving overall usability. This consisted of keeping in mind three points. First adding any functions found to the script that may improve the user experience and allow for greater manipulation of the STC. An ongoing investigative process resulting in the miscellaneous utilities listed in the diagram above. Each function allowing for greater manipulation of the STC scene, adding of info to the scene or capture of the scene in one format or another. Second point was that all functions used should be simplified as much as possible, decreasing user knowledge requirements. This largely consisted of repackaging many standard functions as STC variants where the amount of required user inputs is decreased. This resulted in functions such as *STC_Internal_Visualization_Setup()* described below. Finally throughout the coding process all scripts were to be made as legible as possible by containing a title, general description, specific function descriptions, within function step descriptions and section breaks (see figure 4 below).

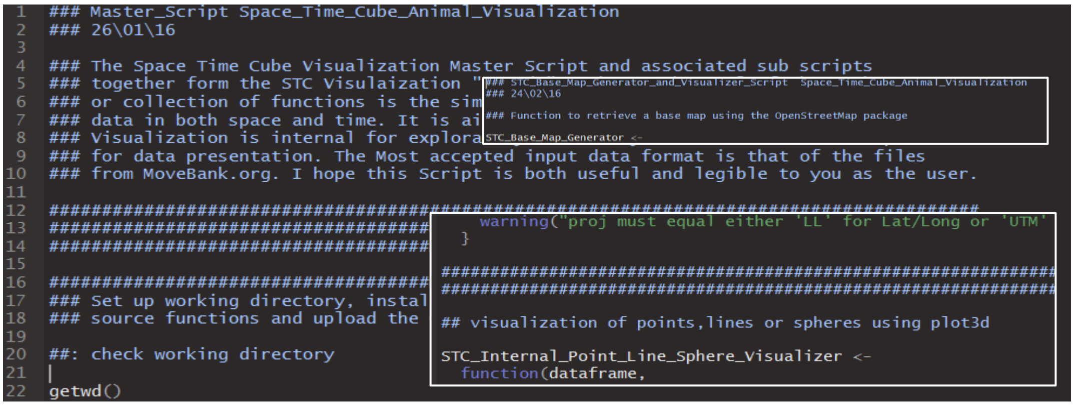

Figure 4: STC Script formatting example

3.2.2 Space-time cube template

To construct a STC in R we mainly made use of the 3D visualization package '*rgl*' . *Rgl* produces a device in which a 2D+/3D visualization scene can be constructed. Objects can be added to the scene multiple times on top of each other as long as they are not of the same type. This made it possible to build a template STC. The packages functionality allowing for subsequent additions. We aimed to combine all the basic requirements of a map and graph into the STC template. This resulted in three main functions *STC_Internal_Visualization_Setup()*, *STC_Base_Map_Generator()* and *STC_Base_Map_3d_Visualizer()*. The first produces the empty STC aiming to include all utilities; bounding box, axes ,labels , title and subtitle. Latitude, longitude and date were auto set to the x,y and z axes respectively The second on the basis of specified latitude and longitude limits retrieves an open source map. The third transforms that open source map by adding z values into a base map for visualization within the STC.

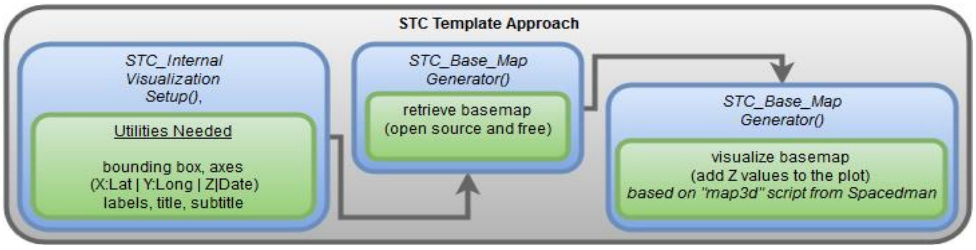

Figure 5: STC template approach and theoretical steps

3.2.3 Individual tracks and interactions

Construction of the first visualization for individuals consisted of building three main functions. *STC_Individuals_Dataframe List_Maker()* for easier access to individual datasets by splitting the original by individual output from pre-processing by individual into separate dataframes and amalgamating them into a list for ease of access. *Distance_Interaction_Calculator()* for identifying interactions. Interactions are identified on the basis of a threshold. If the distance between two points recorded at the same time falls below that threshold then it is recorded as a possible interaction and extracted from the dataframe into a subset. Distance calculation takes between two points takes into account the curvature of the earth. The final function built *STC_Internal_Point_Line_Sphere_Visualizer()* visualizes the input dataframe in a device. For ease of use functionality has been built in so that the user can specify colour shape and symbol (line, point or sphere) making distinguishing between features easier.

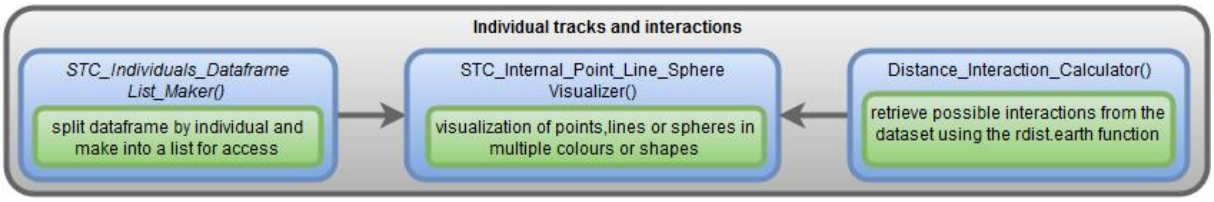

Figure 6: Individual tracks and interactions approach

3.2.4 Population average track and outliers

Construction of the second visualization for a population used four main functions. The first three work together to produce a population track that can be visualized in the STC using the previously described function *STC_Internal_Point_Line_Sphere_Visualizer()*.The first part of constructing the population track consisted of creating a function to calculate the geo centric mid-point from multiple input locations. This was done using equation One. The equation first calculates the necessary values for each location in the dataset. The it aggregates all those values and calculates the geocentric midpoint between all the input locations. This equation is split between two functions both used in *STC_Individual_Averaged_Track Calculator()* and in *STC_Population_Averaged_Track_Calculator()*. The first calculates the midpoint for each individual on each day. Making the minimum required amount of locations per day one. The second uses the data from the first function and calculates the midpoint location between all individuals per day. The minimum required amount of points per day being two.

Equation 1: Geocentric midpoint calculation

$$
\begin{aligned}
&\text{GeocentrecalcPt1} = \\
&(\\
&lat(r) = lat * \frac{\pi}{180} \\
&lon(r) = lon * \frac{\pi}{180} \\
&x1 = \cos lat(r) * \cos lon(r) \\
&y1 = \cos lat(r) * \sin lon(r) \\
&z1 = \sin lat(r) \\
&) \\
&\int_{n}^{x} GeocentrecalcPt1 \\
&x = \bar{x}(x1.list) \\
&y = \bar{y}(y1.list) \\
&z = \bar{z}(z1.list) \\
&lon = \text{atan2}(y, x) \\
&hyp = \sqrt{x * x + y * y} \\
&lat = atan2(z, hyp) \\
&lat = lat * \frac{180}{\pi} \\
&lon = lon * \frac{180}{\pi}
\end{aligned}
$$

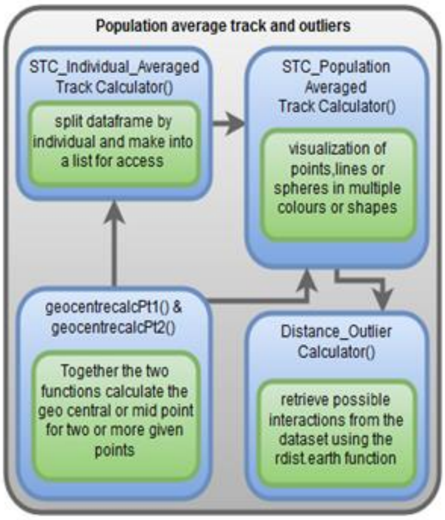

Figure 7: population average track and outliercoding approach

The last function calculates the outliers *STC_Individual Averaged_Track_Calculator()* by comparing the population track points to all the other individual point locations occurring at the same time following the same method used for calculating interactions.

3.2.5 3d polygon home ranges

The final transformation visualization required the construction of two main functions the output of the first used as the input for the second. *STC_KDE_Calculator()* calculated a multidimensional KDE (kernel density estimate). Afterwards *STC_Internal_KDE_Visualizer()* visualizes the KDE home range within the device at 95% and 50% confidence, colour options are again provided.

3.3 Validation

After the framework and implementation process were completed two surveys were constructed so as to answer research question four; *Can the value of the categorical framework and its implementation be assessed and validated.* The choice of two surveys is based on the outcomes of the literature review where two types of surveys were investigated. The value of both evaluations from an operationalist and design perspective (Kraak, 2003; I. Kveladze et al., 2013) (survey one). And comparative evaluations generally with other 2D and 3D techniques (Gonçalves et al., 2014) (Kristensson et al., 2009) (Vrotsou et al., 2010) (survey two) was shown there.

With respect of the structure of the surveys they consisted of multiple choice, yes\no and short answer questions. A question was considered open if it was a short answer question or if other was provided as an option within a multiple choice or yes\no question. The conceptual survey consisted of 3 background questions, 3 general questions and 8 conceptual questions for a total of 14. 6 of the questions were closed among them 2 of the general questions. The exploratory survey consisted of 3 background questions, 7 conceptual questions and 6 exploratory questions for a total of 16. 10 of the questions were closed including 2 of the general questions. Within the validation section of the results chapter a (C) or (O) is listed next to each question to signal if it was open or closed. In this way the reader can recognize when the responders were or were not limited in their answers. All of the questions aside from the background questions asking for general information, the short answer questions and the exploratory questions asking the users to identify a number of objects were based on semantic scales and semantic differentials in the case of yes\no questions. This way we were hoping to get the clearest answers possible and decrease the time taken to fill out the survey. All respondents completed the surveys online. However the user surveys were completed in situ with no extra contact. The results of the validation were processed using Microsoft excel and a summary of how each question was answered provided in the results.

The first survey constructed was targeted at field experts and contained only qualitative elements focused on the conceptual. Specifically the project processes and outcomes. We aimed to confirm the value of our concepts and the legibility of our framework and transformations from an expert standpoint. Our selection process for the first surveys review group consisted of listing the most influential literature pieces and the fields experts who wrote them. We aimed to validate our work using experts from the fields of GIS and Ecology. Then on the basis of access we contacted and sent out our survey with an accompanying explanatory email to eleven individual experts.

The second survey constructed was aimed at possible users and contained both qualitative and quantitative elements focusing on both the conceptual and the practical. Specifically the legibility of the outcomes to non-expert users. We also wanted to confirm the usability of the STC produced using R as an aside. The choice for the second surveys test group was made on the basis of two points, that they had to actually be possible users of the product later and have a basic understanding of the field of GIS or ecology and that they had to be within direct access as the product had to be tested in-situ.

For both the technical testing during implementation as well as the usability tests a dataset was required. We tested out our script on multiple datasets sourced freely from movebank.org. It is important to note that this project focuses on the technical aspects of analysing movement data, therefore biological inferences are not made beyond suggesting the outputs capability in making an inference. Of the datasets investigated we settled on one for our usability testing and surveys, the Swainson's hawk (Buteo swainsoni) dataset[17]. The Swainson's Hawk is a migratory raptor and the data covers the temporal period from 1995-1998 and the spatial region from Alberta, Canada to central Argentina. Additionally the dataset contains 43 individuals many recorded simultaneously. It is for these features that this dataset was chosen as these features make it suitable for the visualization of all the transformations constructed.

[17] Thanks goes to Michael N. Kochert and movebank for access. All rights to the data belong to Michael N. Kochert and company (Fuller, Seegar, & Schueck, 1998)

4. Results

The results are presented in three sections. The first presents the framework produced for research question two based on the outcomes of research question one. The second section presents the technical results of implementation the focus of research question three. All of the visualizations produced through implementation of the transformations are presented. The last section presents the results of the surveys conducted in answer to research question four; validation of the outcomes of research question two and three.

4.1 Framework

Figure 8 shows the strategical framework of transformations produced as a result of answering research question two. A description of how the framework works follows the diagram, The Swainson's Hawk as well as providing the dataset for usability testing is used here to illustrate the frameworks usage within the diagram and in the walkthrough that follows:

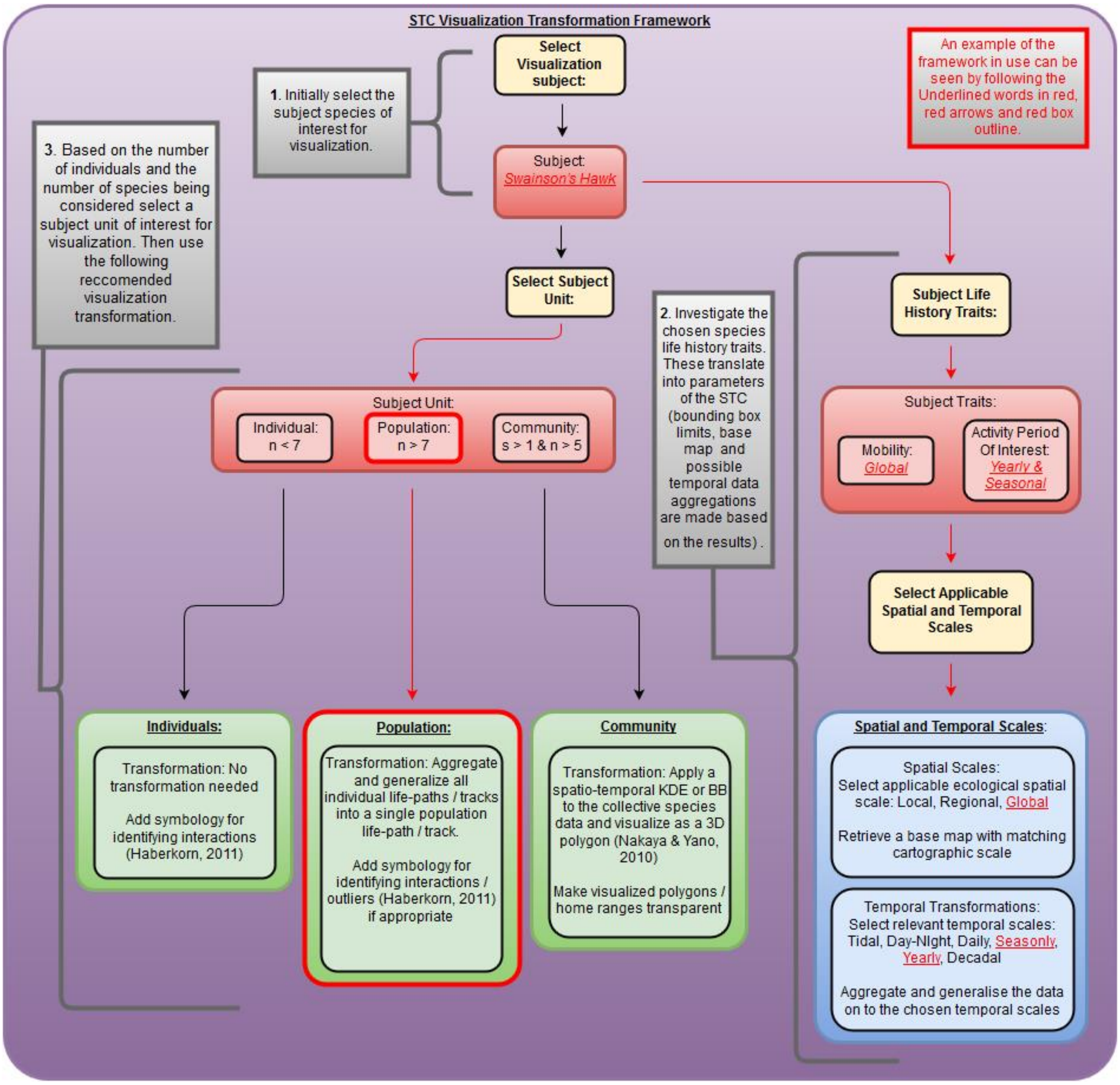

Figure 8: STC Visualization Framework

A user selects a subject to study in this case the Swainson's Hawk. Following the life history pathway they research the life history traits of the subject, specifically activity period of interest and mobility. In the case of the Swainson's Hawk yearly and global. This provides the user a spatial and temporal scale that the STC can be focussed to and provides the transformation direction.

The user similarly follows the unit pathway and researches the subject for the appropriate unit size for visualization. In this case as the dataset contains more than seven individuals (going beyond the working memory threshold (Miller, 1956)) throughout the same temporal period and less than two species making the most appropriate subject unit for analysis population. The transformation listed that follows provides the most appropriate symbology for representing that unit within the STC (population pathway with outliers shown).

The framework pairs the most appropriate transformation technique to each spatial, temporal or unit attribute (see table 3 for attributes). The user is then guided to the transformation that will best represent the animal movement attribute being studied. This is why the walkthrough above follows this path as the information on attributes is required before a suitable transformation can be applied.

Table 3: Animal attributes categorised on the basis of the STC framework

Spatial	Temporal	Unit
Local | Regional | Global	Tidal | Day-Night | Daily | Seasonally | Yearly | Phenologically | Decadal	Individual |Population | Community

Based on the outcomes of the literature review we decided on three different transformations (visualizations) to match the three different unit attributes. With regards to the more varied spatial and temporal attributes a less rigid approach was decided on. All five attributes and the associated transformation can be found in table 4. In the case of the unit attributes a single transformation strategy was applied to each one. While in the case of the spatial attribute types a single transformation strategy was applied to all attributes. The same goes for the attributes of type temporal.

Table 4: Movement data Attributes and associated transformations

Type: Attribute	Transformation (visualization)
Unit: Individual	No specific transformation | Add colour to distinguish between individuals | Add symbology for identifying interactions (Haberkorn, 2011)
Unit: Population	Aggregate and generalize all individual life-paths / tracks into a single population life-path/track. | Add symbology for identifying interactions/outliers (Haberkorn, 2011) if appropriate
Unit: Community	Apply a spatio-temporal KDE or BB to the collective species data and visualize as a 3D polygon (Nakaya & Yano, 2010) | Make visualized polygons / home ranges transparent | Add population track from population transformation for reference (general path)
Spatial: All	Retrieve a suitable base map with a cartographic scale matching the movement data
Temporal: All	Aggregate and generalise the data on to the chosen temporal scales

The result should be a clear and understandable framework presented here as a diagram that should guide a user to the most suitable STC visualization method (found) for their dataset.

4.2 Implementation

The Implementation of the framework resulted in the visualization of three main transformations each targeting a unit attribute. Semi-automatic scaling to an appropriate spatial attribute pre visualization was also achieved. As for scaling to the temporal attribute in this case it was limited to the yearly level. sub setting to a temporal period was made possible however no further functionality was developed in this direction (see the discussion for details). A basic template STC containing nearly all necessary utilities was developed. All code was written and formatted legibly for user guidance. Extra functionality was added where possible. Examples of all cases mentioned are provided.

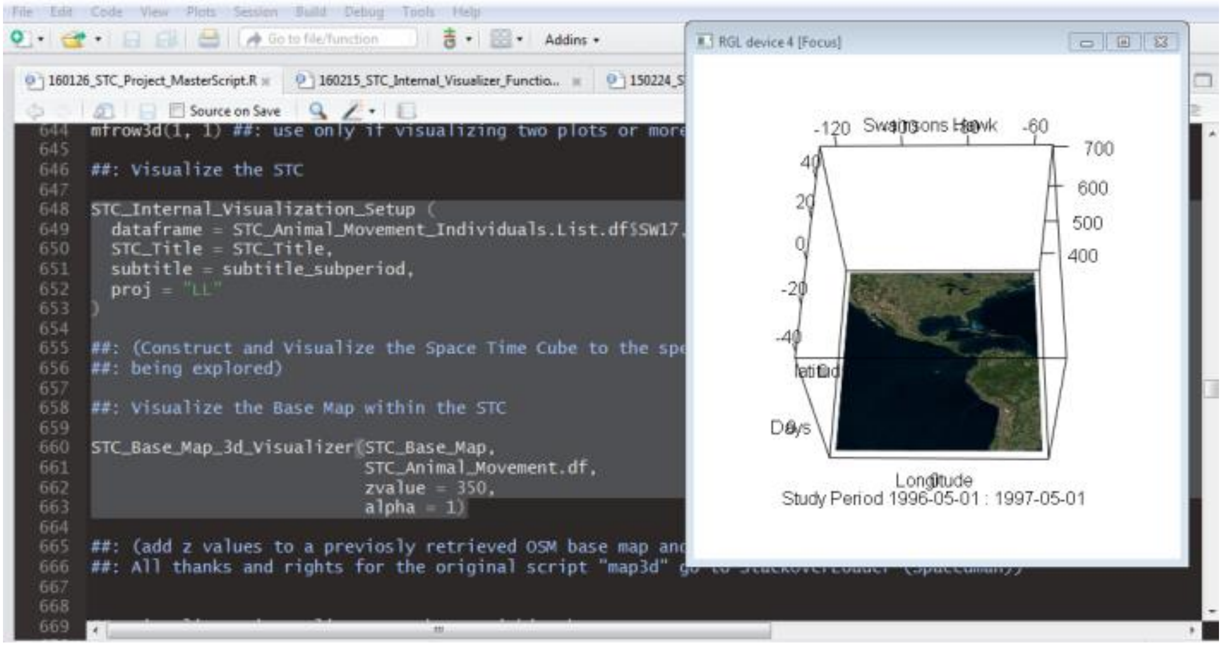

Figure 9: R working environment and code format, with the basic STC template and base map shown in a pop out device

We were able to achieve all functionality aimed for within the basic STC template (figure 9) aside from date on the Z axis. As a substitute we utilised days count(days since start of recording) and developed an alternative method for presenting date info within the STC scene (see figure 14). The capability to present the data on the appropriate spatial scale pre visualization was also developed. The capability to present the data on the appropriate temporal scale pre visualization was not developed. It is on the basis of the STC template that the three unit attribute transformations were based (figure 10).

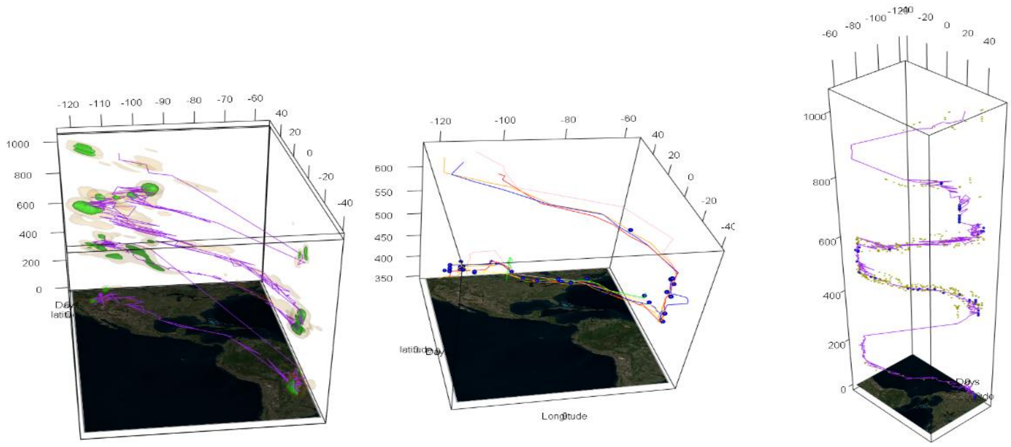

Figure 10: All three STC unit transformation visualizations

For unit attribute: Individual (figure 11). We were able to visualize multiple individual animals movement patterns through space and time. The base map provides spatial reference while the different colour among the lines/tracks allows the user to distinguish between individuals. Interactions as suggested by the framework are visible as blue spheres. A legend is provided in the upper corner and all colours and point shapes have been made adjustable (pre visualization).

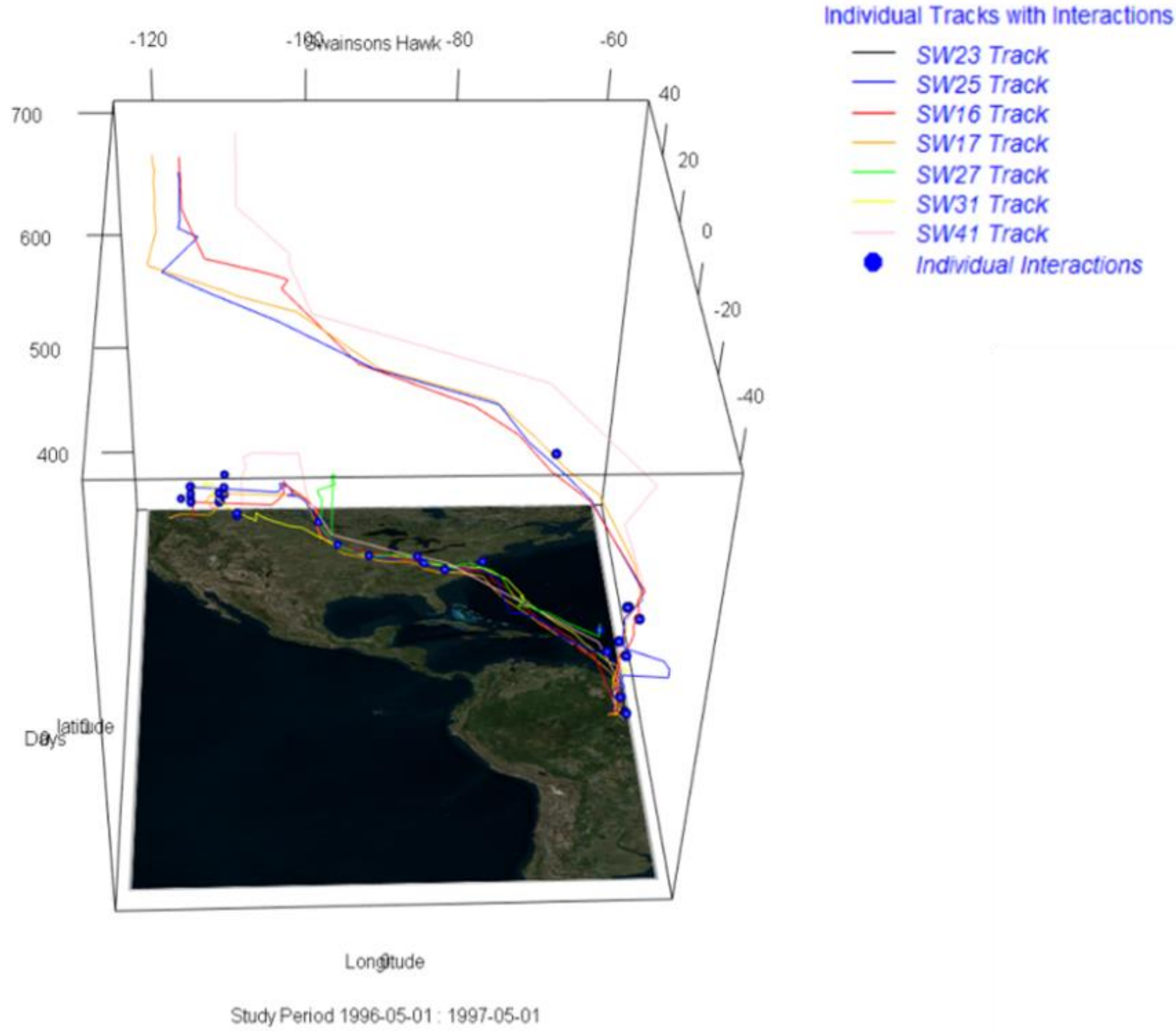

Figure 11: STC Individuals with interactions visualization

For unit attribute: Population (figure 12). We were able to visualize the population line/track. The combination average of all individuals for a given time (minimum of two locations per given time). Further we were able to visualize both outliers and interactions within the same visualizations as defined by the framework. In this case the outliers are presented as yellow squares (tetrahedrons) and the interactions as blue spheres again. Also within the Figure 12 it can be seen that base map can be added at point along the z axis and multiple times. Transparency options also exist for the base map.

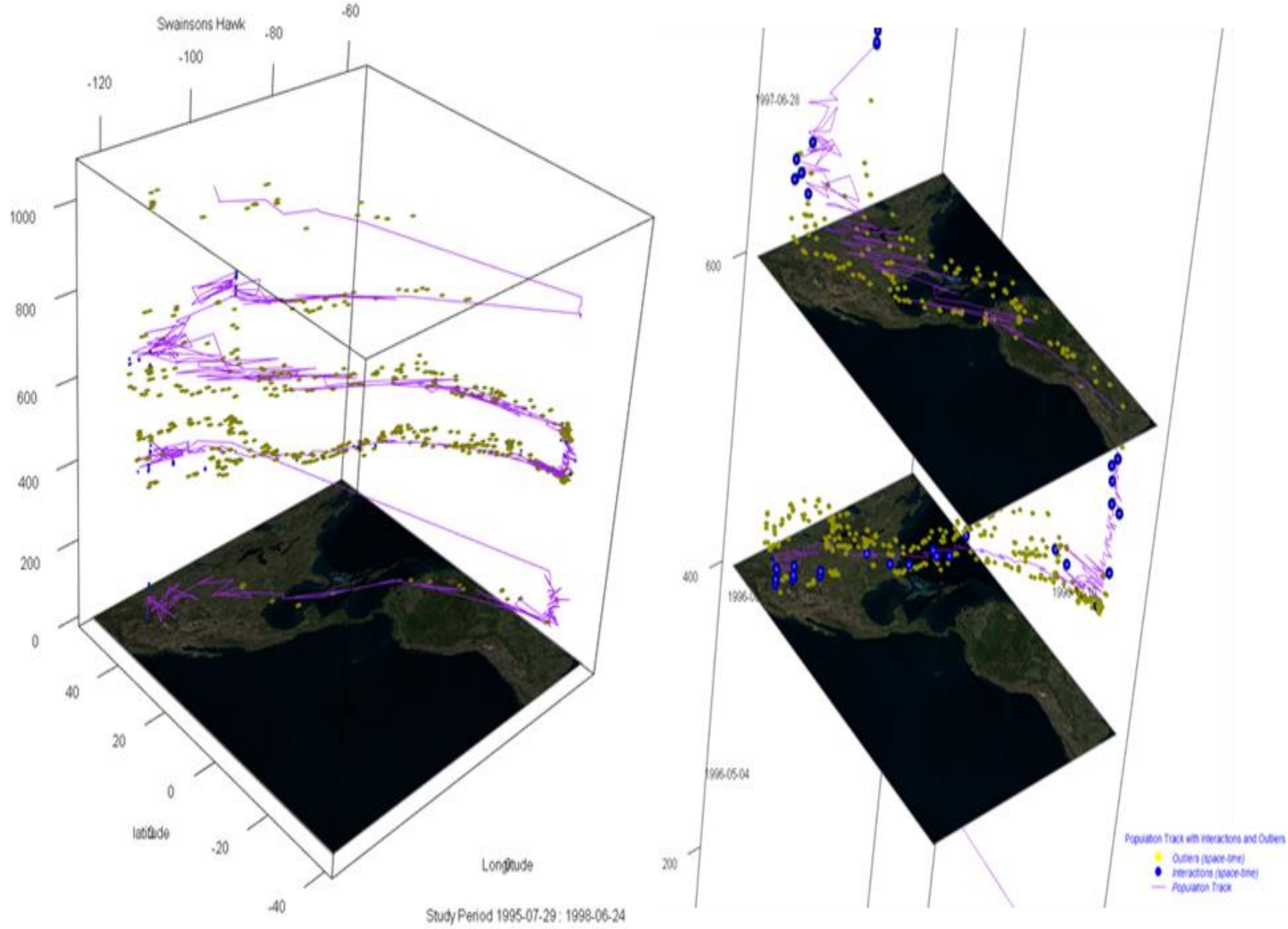

Figure 12: STC Population track visualization with outliers and interactions

For unit attribute: Community (figure 13). We were able to visualize separate home ranges for every non migratory period within the study period as suggested in the framework for the visualization of community movement data. This was done by sub setting the time periods of interest and carrying out separate KDE on each subset (non-migratory periods were selected arbitrarily on the basis of general movement north or south and do not refer to biologically correct time periods). The home ranges consist of both 50% and 95% confidence variations. The population path\track acts as a guide from home range to home range concentration. Again an example of multiple maps added to the STC can be seen.

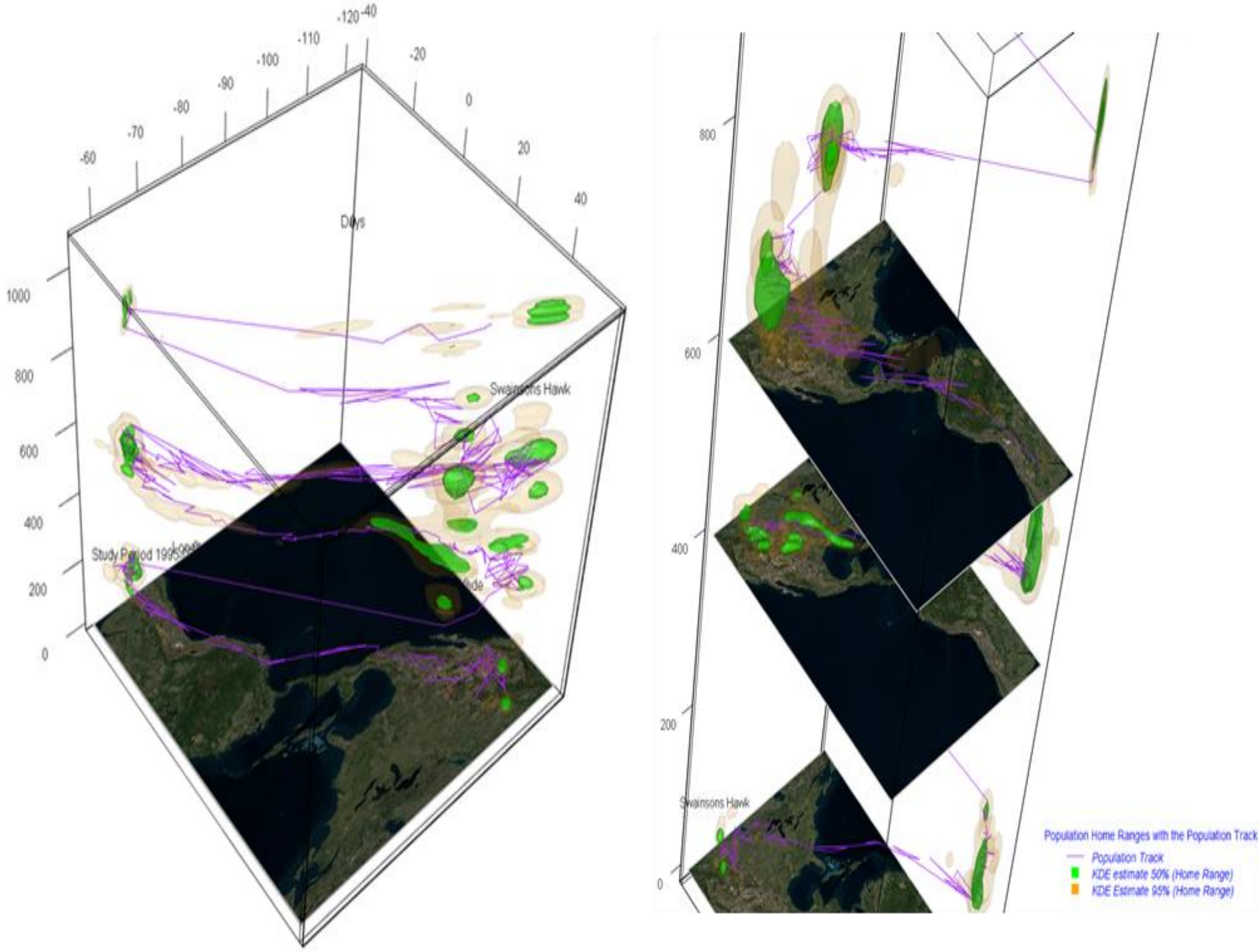

Figure 13: STC KDE home range visualization with population track

The final map (Figure 14) shows many of the attribute transformations presented earlier. It also presents the alternative method of showing date information within the scene. Attaching the info to the points themselves at regular time intervals. Further a 2D variation of the exact same scene is provided opposite with title and subtitle so as to allow for clear comparison and investigation of the data as a whole.

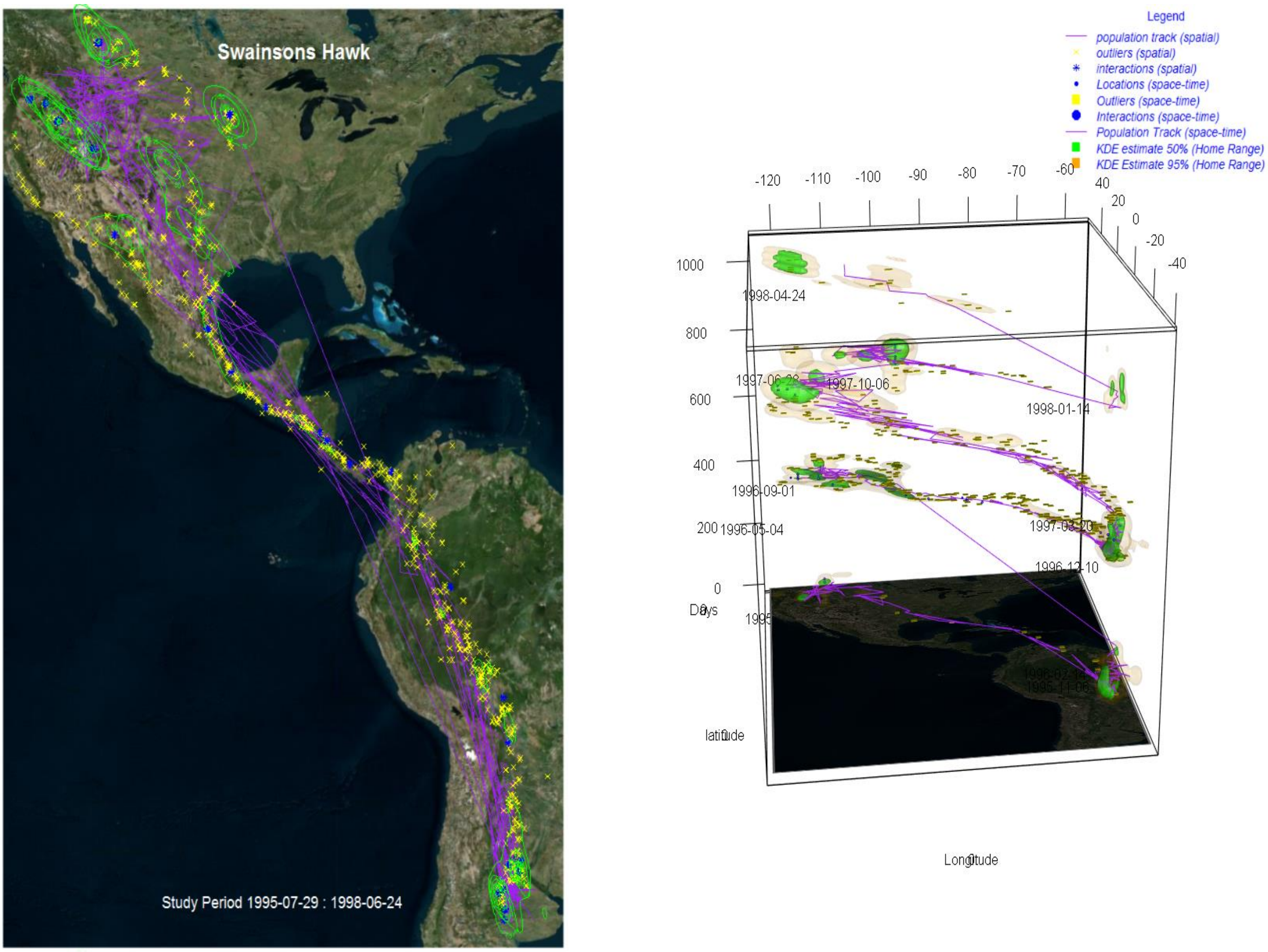

Figure 14: STC visualization presenting multiple attributes (right)and a 2D/top view comparative visualization showing the same attributes (left)

4.3 Validation

Two Surveys were constructed and sent out to validate the outcomes of this project. Outcomes constructed on the basis of research question two and three, a strategical framework for the visualization of animal behaviour and the implementation of that framework. The summarised results of both surveys are provided below. Again a *(C)* or *(O)* is listed next to each question to signal if it was open or closed. An example of the introduction page of the survey can be found in Appendix B The full surveys can be accessed via the WUR[18]. The initial general questions asking users and experts about their background field, GIS and STC knowledge are not provided directly but summarised at the beginning of each subsection.

4.3.1 Conceptual expert survey

The conceptual expert survey had a total of seven respondents. Five GIS experts, an Ecology professional and a professor of computer science. Six of the experts considered GIS there primary field of expertise and one said it was a field they had some experience with. Regarding previous knowledge of the Space-time Cube for five of the experts it was a field of study they had worked in. For one it was a field they were familiar with and for the last they had not heard of the field before.

Do you believe the STC is a good tool for exploratory data analysis of GPS data ? (C)

Of the respondents four considered the STC an effective tool for exploratory data analysis. Two believed it could be if improved and one did not believe it to be an effective tool for data analysis

Do you agree Clutter is the largest issue facing STC usability or do you believe that there is another problem ? (O)

Four agreed that clutter was the largest issue facing STC usage. Another expert said that clutter would not be an issue if trajectories were properly selected and adjusted, suggesting that they do consider it an issue but a solvable one. One expert believed that reconciling the different dimensionalities of space and time was the issue. Another suggested that axes and locations are often misinterpreted or difficult to discern.

Do you agree by making parts of the STC methodology and visualization process uniform in both structure and output, analysis could be both improved and made easier ? (C)

Four of the experts had no opinion regarding this. Two agreed that yes generalisation and standardisation would result in improvements and one thought no. That four respondents had no opinion may suggest that because this was a closed question they were left with no other option.

To tackle the issue of clutter and to improve analytical legibility I designed a framework/guide of transformations to be implemented on any animal data set so as to improve legibility when visualized within a STC. That framework is provided here with an explanation of how it works. Is the framework presented legible and possible to follow ? (C)

Five experts found the framework legible and possible to follow and two found it illegible and could not follow it. (framework shown to experts matches Figure 8)

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[18] The full surveys can be found in appendix B on a DVD within the GIS department of the WUR and are retrievable upon request.

The transformations created based on the framework from before are shown below with a description of each provided. Do you believe a guiding framework such as this can improve the usability of the STC in exploratory data analysis, specifically of animal movement data? (O)

(The transformations shown to respondents corresponds to Figures 10 through to 13)

Three of the experts believed that such a framework as shown could improve STC usability and exploratory data analysis. Three others agreed if it were further improved, improving the axes legibility, combining with other visualizations and improving the explanation. One expert did not agree believing it too complicated for non-expert users.

Do you believe the visualizations above are suitable for representing animal behaviour data or movement data in general ? (O)

Six off the experts thought yes it was suitable. A few on the basis that it would be further expanded upon, made more sophisticated. One answer was unclear but presumed to be a no.

So as to support the growth of STC visualization do you believe multiple competing platforms or a single platform would be best? (O)

One expert believed the question irrelevant. Another user believed one platform was best. Three believed multiple platforms was the best option. The last gave an example of how there are multiple options available currently suggesting that they either had no opinion or supported the multiple platform position.

Do you believe R would serve as a suitable platform for STC coding and visualization ? (C)

Six experts thought R was a suitable platform and one disagreed, stating their reason via the previous question as R is suitable for coding the STC but not for visualisation, because of its lack of interactivity.

Do you believe STC (spatio-temporal) visualization would provide new valuable data exploration capabilities to movebank.org users ? (O)

(The survey answers were given on the basis of figure 15 and a link to the movebank.org page. A variant of this question was given in both surveys.)

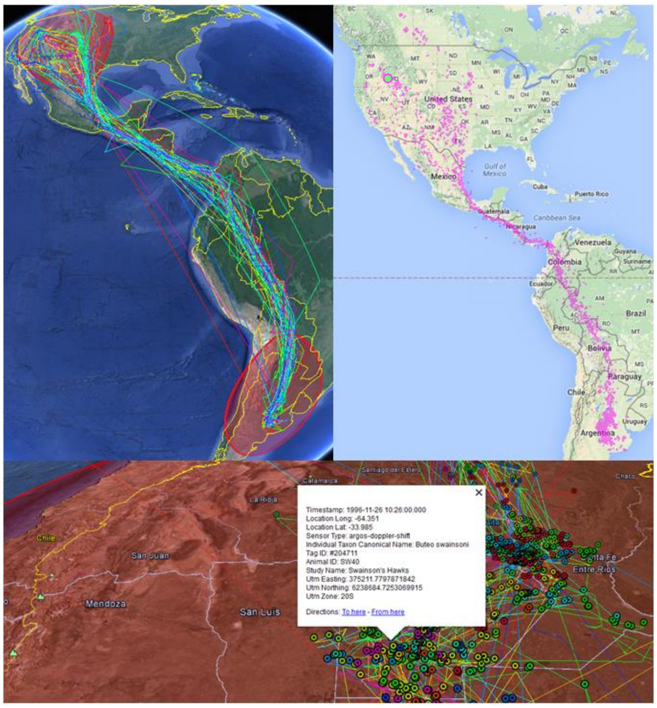

Figure 15: movebank.org visualizations of animal movement from the STC visualization surveys

Four experts believed it would. One disagreed and two thought that it might as long as it was an additional option one amongst many.

Two of the images above are of the available movebank.org kmz's for google earth. Below you can find a video of an STC test case kmz (An STC movement track .kmz) Do you think a space-time cube .kmz such as this holds possible value ? (O)

Three experts thought a STC .kmz would add value. The remaining four thought that it might but that it was hard to understand or contained issues that needed solving first.

Please consider the video of 3D STC visualizations[19]*. Do you believe clutter has been reduced and the legibility of the STC improved via the transformations and adjustments (colour schemes, legends, labels, base maps etc.) applied ? (O)*

Five of the experts agreed that clutter had been reduced. One disagreed and one expert believed it had been reduced but was due to the change in viewing angle in the animation seen in the video not due to any work done with the STC.

4.3.2 Exploratory user survey

The exploratory user survey had a total of 12 respondents. All 12 users identified themselves as GIS students. Nine considered GIS there primary field of expertise and three users identified GIS as a field they have some experience with. Of the twelve nine also considered Space-time Cubes as a field of research they were familiar while the other three identified it as a field they had heard of.

[19] The video may still be found at https://www.youtube.com/watch?v=SKQtfZEh8-o

As a possible user is the framework presented legible and possible to follow ? (C) (framework shown to users matches Figure 8).

All twelve users considered the framework legible and possible to follow

Do you believe a guiding framework such as this can improve the usability of the STC in exploratory data analysis, specifically of animal movement data for users such as yourself? (O)

Seven of the users thought the framework would improve STC usability , one of them believing it too be applicable to humans too. One could not say. The remaining four agreed that it could if certain factors were taken into account. One believed prior knowledge was required. Two thought it was too detailed. The last thought more dimensions may need to be represented.

The transformations created based on the framework from before are shown below with a description of each provided. As a possible user do you understand the concept behind these transformations in general (the concepts the transformations are attempting to represent) ? (O)

(The transformations shown to respondents corresponds to Figures 10 through to 13)

Ten of the users understood the theory behind the transformations on the basis of a description and the images alone. One did not understand the idea behind the transformations and how it could represent animal movement and one understood the first two transformations (individuals, population) but not the home range transformation.

As a possible user do you support R as a suitable platform for STC coding and visualization ? (C)

All twelve users agreed that R was a suitable platform

As a possible user do you believe STC (spatio-temporal) visualization would provide new valuable data exploration capabilities to movebank.org users ? (O)

(The survey answers were given on the basis of figure 15 and a link to the movebank.org page)

Ten thought they would. One thought they would but was sceptical because of their lack of knowledge of movebank and one thought they would as long as other visualizations were also made available.

Do you think a space-time cube .kmz such as this holds possible value as a user ? (O)

Nine users thought yes and three thought no. One of those three users thought it may hold value as a final presentation visualization.

Do you believe clutter has been reduced and the legibility of the STC improved via the transformations and adjustments (colour schemes, legends, labels, base maps etc) applied ? (C)

Eleven of the users believed clutter was reduced while the last user believed that it could be the case if less information was visualized only what was necessary.

At this point in the survey five questions were asked of the user that involved manipulating and using two live STC visualizations. The first two asked the users to count how many interactions they could count in a

3D STC visualization (blue points) and in a 2D image of the same scene (blue crosses) The 2D image was provided first. The users were given the options of 15-20 | 20-25 | 25-30 .The correct answer was 28. A range was given to account for some of the variation caused by the large number of objects visualized.

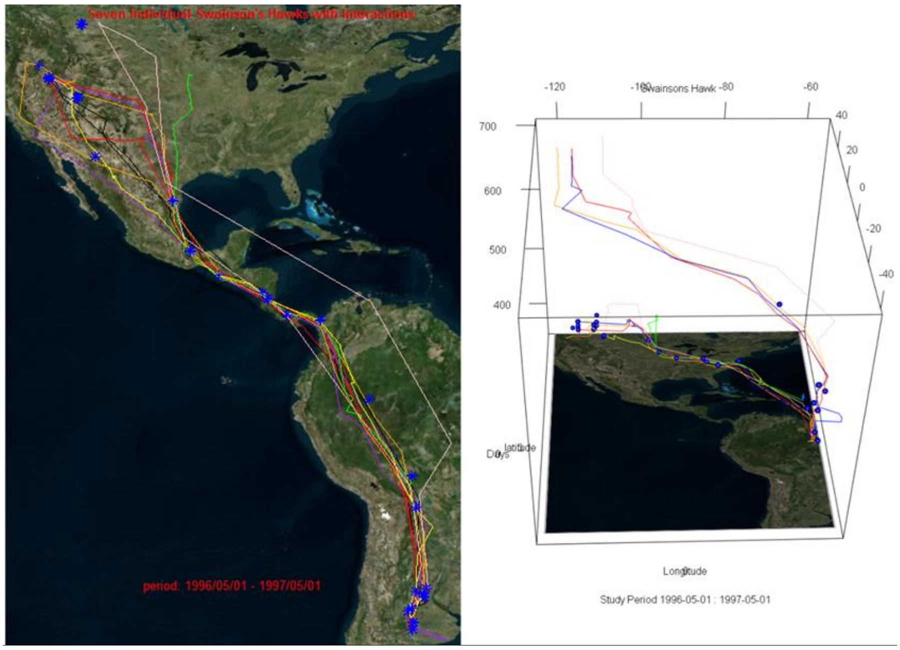

Figure 16: STC Visualization and equivalent 2D Image shown to the users (separately) during the survey to identify interactions

The users were given the options of 15-20 | 20-25 | 25-30 . Ranges were given to account for some of the variation caused by the large number of objects visualized. The correct answer was 28. Generally the users identified the correct number of interactions better in the STC then in the 2D image. The one low estimate of interactions within the STC is of interest and may come as a result of confusion in understanding the STC initially.

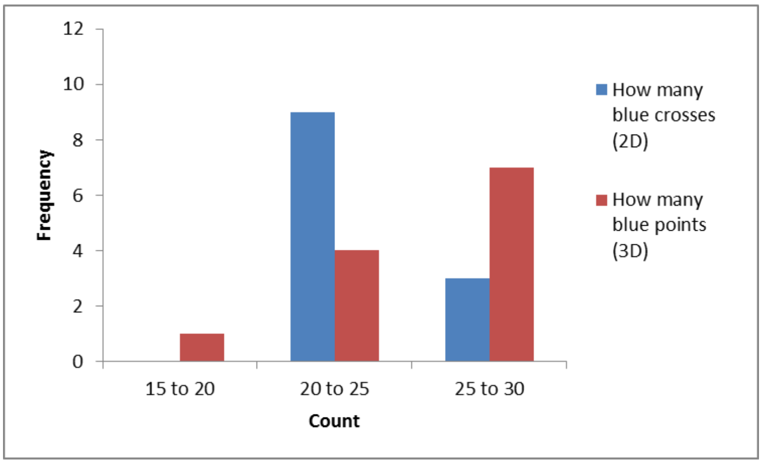

Figure 17: Frequency of count ranges among users for the amount of interactions shown in Figure 16

The following two questions followed the same format however the user was asked to identify home range concentrations, green polygons and circles respectively.

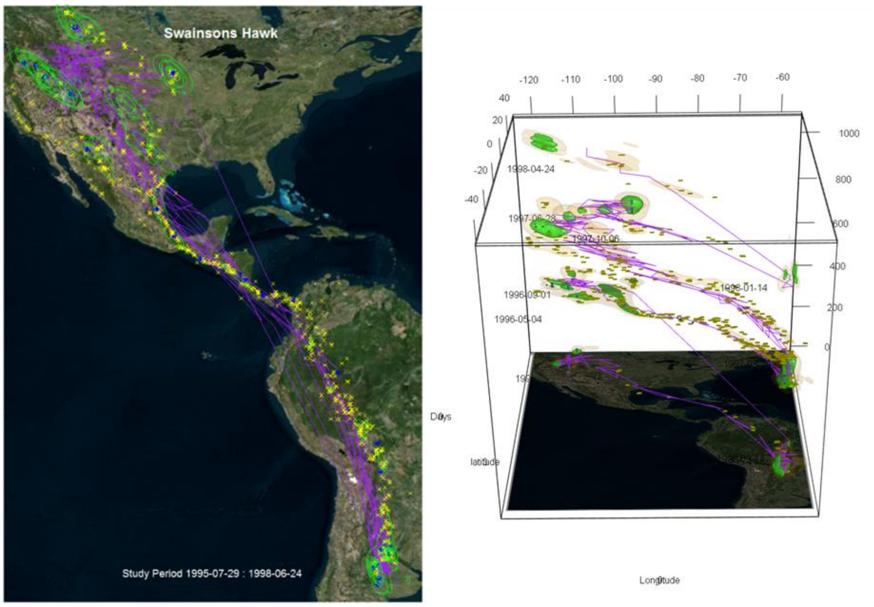

Figure 18: STC Visualization and equivalent 2D Image shown to the users (separately) during the survey to identify home ranges

The users were given the option of 5-10 | 10-15 | 15-20. Ranges were given to account for some of the variation caused by the large number of home ranges being visualized. The correct answer was 18. Generally the users identified the correct number of home ranges better in the STC then in the 2D image.

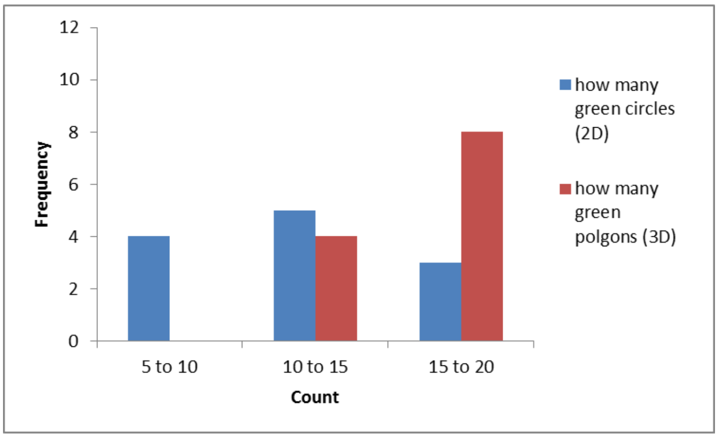

Figure 19: Frequency of count ranges among users for the amount of home ranges shown in Figure 18

In the visualization in Device 1 can you more clearly distinguish between the three feature types (point/individual, line/track, polygon/home range) in the 2D or 3D STC visualization? (C)

Ten of the users found it easier in the 3D STC visualization and two users in the 2D image. (The visualization shown to users matches Figure 14)

Did you find the STC easy to manipulate and use ? (O)

Eleven users found the STC easy to use. One among them suggesting that colour choice of the points made it somewhat difficult. Only one user did not find the STC easy to use.

5. Discussion, recommendations and conclusions

What follows is a discussion of the outcomes of this thesis research. The conclusions of each research question are stated followed by an examination of how the outcomes lie with respect to other works and relevant responses from the validation. The thesis is concludes with recommendations for further research and a concluding statement.

5.1 RQ1 - Concepts and theories

The outcomes of the literature review first of clarified how the STC sits with respect to the fields of GIS, ecology and visualization. A tool produced by visualization that is able to represent ecological animal movement patterns by applying the theories and practices of GIS. The definitions of scale and symbology were clarified with regards to the STC as was their importance in the development of appropriate transformations. We deliberated that an effective transformation would take a movement dataset and transform its graphical representation onto the appropriate scales and into the correct symbols, those most suited for representing the information originally contained within the data. Through consideration of the constraints of Hägerstraand (1970), the questions of Kristensson (2009) and Gonçalves (2014) and the decisions of Orellana and Renso (2010) we concluded that the most appropriate transformations are based on the attributes of the subject being studied. The decisions, questions and constraints facing a subject are influenced by the attributes of that subject, therefore in reverse the attributes of a subject can be used to infer their decisions and further their actions. We identified three types of attributes within the movement of animals; spatial, temporal attributes most often represented via a transformation of scale and unit attributes more often represented by a transformation of symbology. This flow of thought forms the theoretical basis of our later development of a transformation framework. That framework its format, construction and validation being further based on the design stratagems used by Kveladze and the multiscale data structure proposed by Frank and Timpf (I. Kveladze et al., 2013) (Frank & Timpf, 1994). We believe that the theories discussed should help in the reduction of clutter and improvement of analytical legibility through implementation within a transformation framework.

The earlier paragraph concludes and sums up the theories and concepts covered within the literature review as clearly as possible. Yet most but not all the theories investigated within the literature review are mentioned. It is a limitation that there are too many to include within a clear conclusion. Further many of the theories we consider are interpreted by us so as to conform to the requirements of the STC and this thesis. We do provide evidence and reference many case studies throughout the literature review. However the conclusions made above are as far as we are able to tell novel at least in this form. Therefore how do you confirm the validity of a philosophical product? We propose two ways. The first is the responses from within the expert validation relevant to the concepts discussed. The most pertinent questions we asked experts with respect to the outcomes of research question one was if they considered The STC suitable for exploratory data analysis. Six of the seven agreed that yes it was, two of them saying improvements were however necessary. This at the least validates our theory that the STC holds some value. The second pertinent question was if the experts agreed that clutter was the biggest issue facing STC usability. Out of the seven answers four responded with a yes. If we consider this as support for our theory from over half of the experts we can to some extent validate our assumptions. It is of interest to note however that another expert believed that the reconciliation of the different dimensionalities of space and time was the larger issue. Interpreted it means a lack of capability among people to understand the concepts of space and time as represented within the STC. However in response to this we would submit the multiple works that have made evaluative comparisons between 2D and 3D visualizations(Seipel, 2013) (Gonçalves et al., 2014) (Kristensson et al., 2009) (Vrotsou et al., 2010) (Willems et al., 2011). Further we would submit our own exploratory validation that tested user ability to identify features within a 2D and 3D visualization comparatively. The 3D visualization gathered better results. The outcomes of the other researchers also did not fall in support of the expert's theory but neither did they go against it. The general consensus being that although understanding a 3D STC visualization can be difficult with regards to complicated questions the advantages of the tool outweigh the detriments. Comparatively for simple questions a 2D visualization is much more appropriate. The final expert suggested that the misinterpretation of axes and locations is the larger issue. This is a point not considered directly in this thesis though we did build the most suitable template possible (Figure 9). Finally the second way we can validate the assumptions of this thesis is by proving the value of our more practical outcomes that follow and are based on the theories and concepts we discussed here. If the practical outcomes are correct then the theoretical basis that supports them must carry some weight.

5.2 RQ2 –Strategical framework

A single guiding framework of transformations was built on the theoretical principles discussed in the previous section. The format based on the ideas of Kveladze and Frank and Timpf (I. Kveladze et al., 2013) (Frank & Timpf, 1994). The framework guides a user through a series of steps that should result in the most appropriate transformation for the subject (animal movement dataset) being studied allowing for easier interpretation and investigation of the information contained within. A generic use example of the framework would be as such: If one is studying movement data from a population of migratory buffalo over multiple years then the suggestion will be made to transform the track data of multiple individuals into a single population movement track, placed on a regional base map and shown at a yearly scale. By doing this the movement data is represented in the best manner possible for visualization inside the STC and legibility should be improved.

The value of our designed framework was corroborated through the validation surveys. All users found the framework legible as did five out of seven of the experts. When asked if they believed the framework could improve STC usability, by way of improving legibility seven users thought it would and three others agreed that it would if it were simplified further. Of the experts six thought it would with three of them saying further improvements would be required. However we would conclude that our framework on the basis of these views holds definite value for improving the legibility and therefore usability of the STC.

It is of interest to note is that the majority of comments against the framework were regarding the level of detail. This seems to suggest that the level of simplicity and generalisation applied to the framework is still not enough. However in some cases we would argue that generalisation can have adverse effects so how do you achieve simplicity while not losing all too much information. The case in question is regarding a comment made by one of the experts asking why the value of 7 ± 2 for the threshold between identifying a unit attribute as individuals or a population. The value originates from Millers Law (Miller, 1956) that states the value as the limit to how many objects can be considered simultaneously within a human working memory. Yet how does one explain their actions in the framework without providing a detailed explanation. It proves the limit of a framework in diagram form, suggesting that maybe a diagram alone is not enough.

Within the framework the strict delineation between a population transformation and a community transformation is also worth discussing with respect to generalisation. Within our framework we place a clear threshold between a population transformation and a community transformation, more than one species and seven individuals directing a user to a community transformation. Yet through our process we have come to see there are definite limits to such a strict delineation. For instance when considering seven species with only one individual per species, an unlikely scenario where the individual transformation becomes most applicable. And though the framework does suggest that for less than seven individuals it is most suitable it does not specifically include such a fringe case. More importantly in the case of multiple species and multiple individuals or simply multiple individuals a population track transformation is applicable for both scenarios if the species are on the move and making direct interactions. In the same way a home range community transformation is applicable to both scenarios if the interactions are more territorial or the subjects are moving within a restricted area. The transformations are therefore more generally applicable then first intended. Our goal in the construction of the framework was to guide users to the most suitable transformation for their subjects. Our interpretation that guiding a user consisted of making the framework as rigid and therefore clear as possible may have limited our final results applicability. On this subject the responses of some of the experts were of considerable interest. When asked if making the STC methodology and visualization process uniform analysis would be improved. One disagreed while two agreed. However more importantly the question had a closed design and the remaining four experts stated that they had no opinion, suggesting that they may have limited to this option. Yet the general feel of the responses seems to support the idea that too much rigidity in the framework may well limit the frameworks applicability.

While designing the framework we largely based our design process on the work of Kveladze (I. Kveladze et al., 2013) building a conceptual model through the literature review before building a formal model in the diagram. We did not use usability engineering or in situ usability analysis however. In our defence having access to domain experts to validate our work in situ was not a feasible option. However using a variation on usability analysis or utilizing a more iterative design as proposed in computer systems (Gould & Lewis, 1985) was feasible. It is interesting that the same paper by Gould (1985) goes into reasons why designers as in this case try to get it right the first time by relying on design principles and ignore the value of an iterative approach; stating such cases among others as a belief among designers that user do not know what they need, that guidelines are sufficient and that user diversity and reasoning capabilities are overestimated or considered similar to the designer themselves. In the case of this research we may have been prone to some of these factors ourselves. We may have produced a better and more legible framework if we had utilised an iterative process of modifying, testing and. This is compared with the approach used of getting it right the first time by relying on design principles and validating the final product. The importance of an appropriate design approach is a point well worth future consideration.

5.3 RQ3 Implementation and visualization

Implementation of four out of five of the transformations proposed in the framework was carried out within the open source program R. We were able to construct the continuous transformation that zoomed to the appropriate spatial scale within the STC template (Figure 9) and we built the three transformations for the categorical unit attributes (individual, population and community). The first for individuals with interactions (Figure 11) the second an aggregated population track with outliers to take into account the loss of information as a result of aggregation (Figure 12) and the last for home range concentrations and a population track (Figure 13). Further we were able to improve legibility by providing 2D top view comparison maps (Figure 14) as well as a multitude of other functionalities. The value of our transformations was confirmed through the validation responses. Six of the experts thought the transformations suitable for representation of animal movement data. A few on the basis that further sophistication and development is undertaken. Of greater worth in our opinion is that ten out of the twelve users understood the general ecological premises behind the transformations based solely on the images presented and a short description.

This response among users is also of considerable interest for another reason, as all users tested had a GIS background. Their basis for understanding the ecological concepts behind the visualizations being GIS orientated. It would be of considerable interest to see if ecologist users could understand the visualizations to the same extent. This would shed some light on whether the greater limit to STC usage is a limited understanding of the concepts it is trying to represent or limited understanding of the spatio-temporal concepts that allow it to function.

Turning to the more practical aspects of implementing the transformations there are some aspects of the process worth discussing. First is that the selection of migratory periods was arbitrary and could not be scripted and requires user input. Migration is a mutable variable, the time period at which animals undertake migrations varying among species. We selected arbitrary values as our goal was technical, proving that the transformation functioned and that visualization was possible. This issue of user input is one that comes forward often throughout the process and limited how automated the script could be made. Our inability to visualize the proposed temporal transformations from Andreinko and Andrienko (Gennady Andrienko & Andrienko, 2011) however was limited not due to any technical factors but simple time constraints as we decided to focus on the more interesting and animal movement orientated unit transformations.

Comparatively there are other functionalities that simply did not work out. We were unable to develop a Brownian bridge 3D home range visualization as at this time it seems R is limited to the 3D KDE. Another function that calculates UTM coordinates, Northing, Easting and UTM zone of an input dataset works effectively however subsequent visualizations just would not produce an understandable result within R. The issue did not lie with our calculation as the both the original UTM coordinates for the Swainson's Hawks were visualized as well as our own calculated ones for comparison and they matched. This is also why the UTM function is still included within the repository as it functions fine. However subsequent visualization did not. In the case of the Swainson's, Hawk we believe it may be due to the large amount of UTM zones involved resulting in a misrepresentation of the flight path (Figure 20). We reattempted the visualization with a dataset of African buffalo contained within a single UTM zone and the results were more representative matching the Lat Long output considerably (Figure 20). However in both cases we were also unable to visualize the reference base maps in UTM coordinates. Due to this issues and time constraints we decided to move on as Lat\Long coordinate visualization was working fine.

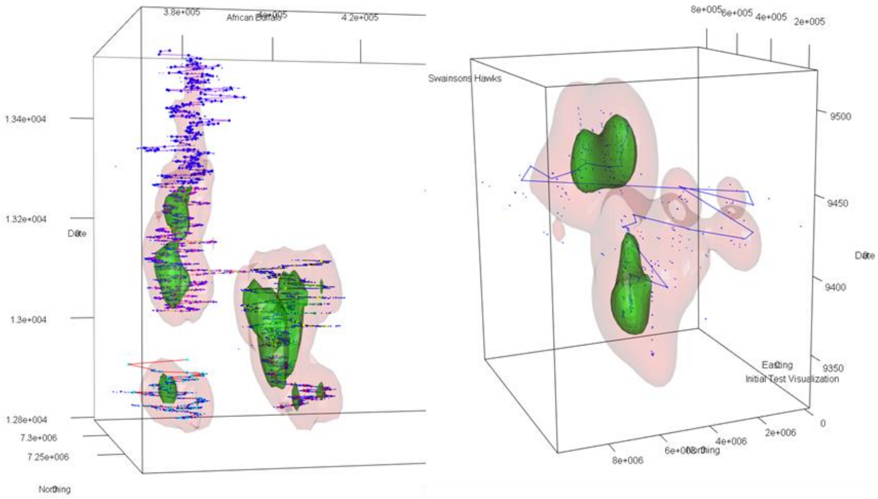

Figure 20: STC visualizations illustrating the issue of visualizing UTM coordinate data, the left map is of African Buffalo and the right map of Swainson's hawk's both in UTM coordinates.

Within the scripts there are also some processes undertaken worth consideration. One such was the issue of the influence caused by having a single point per unique time stamp. Aggregating points for the population track\line transformation when only one point is available is unrepresentative of an aggregated population track and resulted in the inclusion of outliers in some cases (see Figure 20). To make sure the population line is representative the presence of only a single point for a given time meant that it was excluded. However this does mean that they were also excluded from the possible outlier pool as that calculation compared points per unique time against the population line to find possible outliers. So if there is no point in the population track dataset for a given time then no comparison can be made. To overcome parts of this issue the points were first aggregated by day per individual so as to decrease the amount of time stamps with only a single point and generalise the data. Many such small issues what we could call logic coding occurred within the pre-processing of the data most to do with organisation. The single point influence case is only the most dramatic.

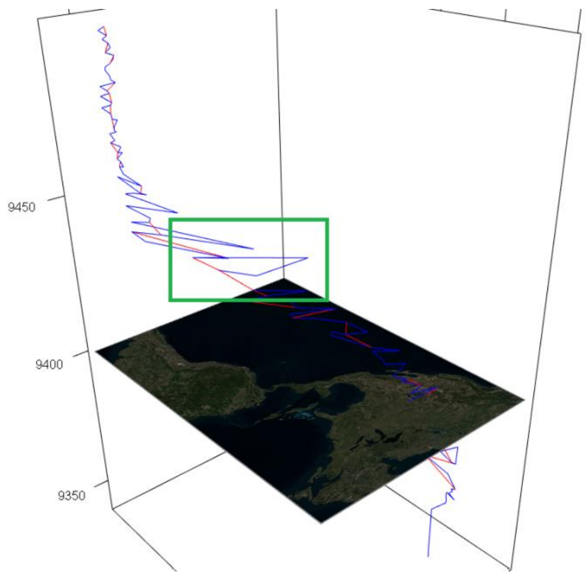

Figure 21: STC visualization showing the influence of a single point on an aggregated population track (red line excludes single points / blue line includes single points)

The single point case leads in well to subject of data limits within this project as a result of limited data access. This project relied entirely on freely accessible datasets and we are very thankful for the datasets from movebank.org. However only the Swainson's hawk dataset contained the amount of simultaneously recorded individuals and data points needed. As no two species with the same local could meet these requirements the true community visualization could not be implemented. That is the visualization of two interacting populations with possible overlapping territories and direct interactions, such as the relationship between migratory caribou in North America and the wolves that follow them. This reveals a serious limitation of this tool as the datasets required need to be quite large for any visualization transformation beyond the individual level.

Finally we want to quickly consider R the platform of implementation. For us as a coding platform it was more than suitable and though issues were present most could be overcome. R provided multiple packages for visualization pre-processing and functionality resulting in many extra functions as discussed earlier, a full list of which can be found in appendix C. Further the freedom of R allowed us to simplify the functions as far as a possible making it easier for users to use. We were not able to implement a GUI interface using the R package shiny but the option exists. If R was overall a suitable platform for this project we would say yes and the validation would agree. Of the experts six considered R suitable for coding and visualizing the STC, the remaining expert considered R suitable for coding but too lacking in interactivity for visualization. A response I understand after working within R myself. Of the users all considered R a suitable platform.

5.4 RQ4 Validation

We would consider the validation a definite success. The responses obtained regarding the entire process helped to further validate most if not all of our outcomes. Most of the respondents saw the value in the work that we did with multiple positive responses. Some of the most important of which was that the majority found the framework legible and the transformations created of use and nearly all agreed that clutter had been reduced using the transformations developed, major focuses of this thesis. The use of two surveys was also a success worth special mention. By utilising the ideas from operationalist and design perspective evaluations as well as 2D and 3D comparative evaluations (Kraak, 2003; I. Kveladze et al., 2013) (Gonçalves et al., 2014) (Kristensson et al., 2009) (Vrotsou et al., 2010) the coverage in answers obtained was much greater. One survey aimed at experts validating the concepts behind our ideas the other aimed at possible users validating general understanding of our ideas, while both validated our products.

We did however identify limitations to our survey that become visible in retrospect. The major one being that using closed structure questions in some cases limited the answers responders could give. In some cases this was good as it resulted in a clear answer however in other cases it limited the value of the responses as in the case when four experts had no opinion regarding generalising STC structure. Closed responses such as this suggest that if closed questions are used they need to be formulated thoroughly so as to give the responders all the options possible.

5.4 Recommendations

Further research and development of a STC exploratory data analysis tool for the study of animal movement patterns should take into consideration the following points:

With regards to the framework it should be redesigned using a more iterative process using the current format as a base line. The structure could be made slightly less rigid and it should be noted that the community and population transformations are applicable to each other's situations. Further (Based on Millers Law) should be placed within the individual's selection box as a form of immediate explanation for the threshold provided (Figure 8). However based on the outcomes and the work of Gould (1985) this is not enough and a clear walkthrough and explanation of the framework diagram should be provided to users as a secondary option.

With regards to implementation in the immediate future the temporal transformations from Andrienko and Andrienko (Gennady Andrienko & Andrienko, 2011) should be developed. Also visualization for a Brownian Bridge or other alternative to KDE 3D home range estimates should be looked into. Finally the development of a shiny GUI interface should be considered. Other options to consider when they become more feasible in R or on an alternate platform is the development of roll-up and drill-down functionalities (Javed & Elmqvist, 2012)and coordinated multiple views (CMV) or composite visualization views (CVVs). One of the issues with R listed by an expert and with the visualization as a whole by users and experts alike is the lack of comparative (interactive) views such as CMV that if available would make analysis easier. However R does not have the capabilities for this currently making maintaining multiple platforms for STC visualization important. Finally another possible future product is a STC kmz. They are of little value currently as the lines do not take into account the curvature of the earth and are not set too any scale however if this can be dealt with they may provide an interesting visualization and presentation medium in the future.

With regards to future validation I would only suggest that both open and closed questions are more thoroughly thought out and the process is undertaken more often so as to make the entire design process more iterative resulting in a more user friendly and targeted final product.

This thesis project focused on achieving specific goals. Yet beyond them our hope for the future is that the outcomes of our work may help in the development of a STC tool for the exploratory analysis of animal movement data on a free platform. The suggestions above will make that easier. The eventual tool is not advocated as the best or only option but simply one among many. The STC is not the only analysis tool available and nor is it the best in every situation but it should not be overlooked and should definitely be represented. The value of a tool based on the STC visualizations and framework we developed is clear and worth future consideration. A product such as this could be linked to the movebank.org site and their thousands of users providing them with new capabilities to visualize and analyse their datasets, providing mutual befits to both the R community and movebank.

5.5 Conclusion

We aimed to improve the analytical legibility of animal movement visualized within the STC using a transformative framework and although there is still much to be done we would consider our aims met. The transformation framework we produced is legible to most users and guides them through the process of choosing a transformation suitable for the visualization and interpretation of their movement dataset. The assumptions of the framework are supported by a thorough literature review that clearly defines all the concepts produced and assumptions made, providing evidence for the ideas they are originally based on. Of the five transformations proposed four were implemented and visualized within the STC using the platform R and have been identified as being understandable, clear and most importantly resulting in the reduction of clutter. Though there is still work to be done we do believe we have achieved our goal of taking a step towards reducing clutter and improving STC legibility through our visualizations and framework.

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7. Appendices

Appendix A (DVD Description)

On the DVD all data related to this thesis can be found split among several folders formatted as follows:

- Reports
- Presentations
- Data
- Figures and Results
- Scripts
- Validation
- Literature

Appendix B (Definitions)

Framework of strategical transformations – In the context of this thesis is; a structured set of strategically chosen data transformations each one aiming to best interpret and visualize a different type of space-time animal movement within the space-time cube.

Framework – A structural plan or basis for a project.

Strategy – A plan, method, or series of manoeuvres or stratagems for obtaining a specific goal or result.

Capability – an individual's capability for movement within the limits of time and space

Coupling – limits on an individual's location within space and time due to events that require proximity to other individuals

Authority – locations that have limited access not due to capabilities but due to the territorial influence of other individuals. Adapted from (Hägerstraand, 1970).

Simple / Elementary Questions – Questions of what, where and when often involving metric properties, situations where space and time can be considered separately

Complex / General Questions – Questions that linked where and when as well as how and why and often involved ordinal properties, an understanding of the datasets spatiotemporal structure is usually needed. Adapted from (Kristensson et al., 2009) (Gonçalves et al., 2014).

Symbology – The transformation of one graphical representation of a dataset into another for ease of visualization and interpretation of the original info does not specifically have to be a geo-dataset

Scale – Total amount of levels within a visualization and the amount of progression between them with regards to the presentation of info (a graduated series)

Zoom – Sub category related to scale, the depth of information presented per level and the ease of change between levels within a scaled visualization
Rendering – Sub category related to both symbology and scale, amount of detail presented per visualization level. Adapted from standard dictionary definitions and (Frank & Timpf, 1994).

Population – A group of organisms of the same species that coexist together within the same spatial location.

Community – A group of different species populations that coexist within the same spatial location. | Ecosystem

Strategical decisions – Decisions regarding destinations and future aims / activities (future planning / forethought).

Tactical decisions – choosing what route to follow that day and response to unexpected events.

Operational decisions – choosing to take the next step or bite, intuitive motor control actions. Generalised here to all animals and adapted from (Daniel Orellana & Renso, 2010).

Pair-wise Interactions – Individual-Individual.

Environmental interactions – Individual-Environment.

Collective Interactions – Multiple Individuals. Direct from (Daniel Orellana & Renso, 2010).

STC Clutter – A build-up of space-time objects within a Space-time Cube during visualization of a large dataset. The resulting visualization is beyond the capabilities of a humans working memory to interpret. Leading to impaired exploratory data analysis

Spatio-temporal animal behaviour – An action taken by an animal that results in a pattern across both space and time simultaneously, given a certain extent in space and time. Measured at the necessary spatial and temporal resolution for recognition of the pattern and visualized at the most appropriate scale for identification and analysis.

Appendix C (Literature Summary)

<table>
<tr><td colspan="3">Paper: Hägerstraand, T. (1970). What about people in regional science? Papers in regional science, 24(1), 7-24.</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">Summary: Hägerstraand considers the status of approaches in the analysis of regional city sciences. He gives specific consideration to the aspects of space and time and how they should be considered simultaneously not separately or to exclusion of one over the other. In specific Hägerstraand applies his viewpoint to the concept of life paths. Used to signify an individual's activities over a specified area and time the exclusion of time in their representation at the time of the paper was non-representative of reality. To overcome this Hägerstraand suggests the use of a space time web (the forerunner of the space time cube) where time is included as a visible dimension. He goes on to discuss how it would work and three categories of constraints (capability, coupling and authority) and how they limit, influence and direct movement within the space time web. After discussing each constraint in relation to space time he finishes by describing how a life path constructed on the basis of a space-time web should be applicable to any aspect of biology beyond simply man. He suggests that with this set up reasonable simulations could be made to help estimate social organization if the technological forecasts of the time are fulfilled.</td></tr>
<tr><td>POI: gives consideration to how basic assumptions at household levels may affect principles of central place theory</td><td>Applicability is that the same idea of basic assumptions can easily be applied to the effects of scale and symbology on basic assumptions made on an animals movement.</td><td>+</td></tr>
<tr><td>POI: Suggestion of the space time web – the first instance of the space time cube that would follow it.</td><td>The space time cube is the main focus of this study and understanding the reasoning behind its creator is definitely of value.</td><td>+</td></tr>
<tr><td>POI: The three constraint categories suggested by Hägerstraand; capability – an individual's capability for movement within the limits of time and space, coupling – limits on location within space and time due to events that require proximity to other individuals, authority – locations that have limited access not due to physical movement capabilities but due to the influence of other individuals on territory.</td><td>Hägerstraand three constraints provide a suitable framework by which to consider limitations within the space time cube as well as formats aggregations of movement and therefore scale and symbology.</td><td>+</td></tr>
<tr><td>POI: Large focus on the human social aspects due to the nature of the subject.</td><td>Certain points discussed do not carry over to the framework that is being aimed for within this thesis. Such as the influence of telecommunications on user movement.</td><td>-</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">Conclusion: Hägerstraand proposes the space time web as a method to investigate movement and life paths within time and space. Discussing that there are three categories of constraints that highly influence movement in terms of time and space and that any presentation using the space time web should take these into account. He concludes that it would be a useful tool if combined with suitable statistics while keeping in mind biogeography. Further he considers it widely applicable to all biological fields and a tool that when technology improves would be utilisable to all geographers.</td></tr>
</table>

Figure 22: Literature Summary Exemplar

Appendix D (Validation Survey)

Space Time Cube Visualization: Exploratory Analysis of Animal Beha... https://docs.google.com/forms/d/1SAEVkl7DhwxSHIm7fbmQz7Er0...

Space Time Cube Visualization: Exploratory Analysis of Animal Behaviour

Dear Participants,

Thank you in advance for taking the time to consider this survey. It is a validation of my thesis as part of the Masters Geo-Information Science program at Wageningen University, Netherlands. My Thesis; Visualization of Animal Behaviour within the Space-Time Cube: Utilizing Applied Scale and Symbology so as to Improve Legibility, considers the application of the Space-Time Cube (STC) to the analysis of animal behavior, specifically movement. STC usability is a subject that has been considered previously with results revealing both evidence in support of the STC as an application as well as identifying multiple issues. So as to further research within this field my thesis extends beyond identifying the basic applicability of the STC, to recognizing those issues and confronting them. The main issue focused on is clutter and via that legibility, platform accessibility is also considered to a small extent. The results of my work are reproduced here. I hope that by taking the time to fill out this survey you can aid me in the validation of my work. Showing that through my methods the issues facing the analysis of animal movement within a STC are reduced.

Background Information on Space Time Cubes (to be read only if needed)

Animal movement takes place in space and time simultaneously. The Space Time Cube or STC uses a three dimensional space or box to present spatio-temporal (space-time) data to the user. In it the third (Z) axis that usually represents height is used to represent time. So that if an object or animal represented by a point or line moves upwards in the box that means it is moving through time. The Space-time Cube originates from Space-Time theory and the original idea of the Space-Time Web. Hägerstraand a social geographer of the 1970s wanted to consider regional social geography and peoples place within it from a new and novel perspective (Hägerstraand, 1970). To do this he suggested the concept of the Space-Time Web. He believed that time and space are not separate entities and that consideration of one could not occur without consideration of the other. The space time cube as we know it developed form this initial theory, modern computing allowing for visualization in real time. The STC uses a three dimensional space to present spatio-temporal data with the third (Z) axis being used to present time instead of elevation (height).

Survey Format and the Test Dataset

The questions are split into three types. Three background questions. six conceptual questions regarding the STC in relation to the goals of this thesis. Finally seven exploratory questions. This is undertaken using the space-time cubes presented in the survey. The test dataset used originates from movebank.org the Swainson's hawk (Buteo swainsoni). The Swainson's Hawk is a migratory raptor and the data covers the period from 1995-1998 and the region from Alberta, Canada to central Argentina. Further the dataset contains 43 individuals with many recorded simultaneously. This project focuses on the technical aspects of analyzing movement data not making biological inferences. Based on this the Swainson's dataset meets the requirements for this thesis.

The survey should take no more than 10-15 min

Regards and thanks again for taking the time to consider my work,

Roeland de Koning

Thanks goes to Michael N. Kochert and movebank for access to the Swainson's Hawk dataset:

Fuller, M.R., Seegar, W.S., Schueck, L.S., 1998. Routes and Travel Rates of Migrating Peregrine Falcons Falco peregrinus and Swainson's Hawks Buteo swainsoni in the Western Hemisphere. Journal of Avian Biology 29:433-440.

Wikelski, M., and Kays, R. 2016. Movebank: archive, analysis and sharing of animal movement data. Hosted by the Max Planck Institute for Ornithology. www.movebank.org, accessed on

1 of 13 15-4-2016 15:33

Figure 23: Opening page of the exploratory user survey

Appendix E (Coding Summary)

Table 5: STC R Code Guide Part 1 (pre-processing and control)

Script	Function	Input	Process	Output
Master_Script Space_Time Cube_Animal Visualization.R	*rgl.open() | rgl.close() | rgl.clear() | rgl.cur() | rgl.quit()*	none	RGL package functions that allow for manipulation of the current scene (in our case an STC) that has been visualized within an R device. In order: open new device, close current device, clear current device (reset), select current device. and quit the entire rgl device system	change in the new or open scene
	rgl.snapshot()	opened visualized scene required (has to remain open)	take a snapshot of the current open device scene (png or pdf)	png snapshot of the scene
	writeWebGL()		write the current scene to HTML: for online web viewing and access	web viewable output odf the scene (html object)
	play3d()		Automatically spin and rotate the visualized device scene for a set period of time	the scene spins
	movie3d()		make a GIF movie of the visualized scene (requires imagemagick an external program) ifimagemagick is not available it can still produce all the snapshots for the GIF. Combining can be done externally afterwards	a GIF file or multiple snapshots of the scene
	Mfrow3d()	parameters (n,n)	visualize multiple plots within a single scene	cuts the scene into subsections
STC_movebank_CSV _to_dataframe.R	*STC_Movebank_CSV toDF()*	movebank or other csv file (containing at a minimum (identifier | lat | long | time)	Opens CSV files and writes them out as a Dataframe with columns relvant to the STC retained. Specifically aimed at movebank.org files and their format	a dataframe with all neccescary data included and the correct formatting for use in all the other functions
STC_Time_Period_S elector.R	*STC_time_period_s elector()*	dataframe* and time period (t1 & t2)	Selects Period of interest to the user for study and subsets the dataframe to that period for further manipulation	subset of the original dataframe
STC_Individual_Ave raged_Tracks.R	*STC_Individual_Aver aged_Tracks_Calcul ator() (uses geocentrecalcPt1 & Pt2)*	dataframe* and time period (t1 & t2)	Calculates the Individual averaged tracks for multiple individuals from multiple dates from a given dataframe (data location is averaged for each individual to a single day)	individual averaged tracks dataframe
STC_Population_Av eraged_Track.R	*STC_Population_Av eraged_Track_Calcu lator() (uses geocentrecalcPt1 & Pt2)*	dataframe* and time period (t1 & t2) (output from STC_Individual_avera ged_tracks generally)	Calculates the population average track from multiple individuals for a given dataset (follows Individual averaged script generally) (average location for a population on a given day is calculated)	population averaged track dataframe
STC_Reproject_LatL ong_to UTM Functions Script.R	*STC_UTM_Calculato r()*	dataframe* with lat\long coordinates	Takes an input dataframe of Lat/Long projection and transforms it into UTM projection (adds UTM Zone, Northing and Easting) *(Thanks and rights for the original script go to Josh O'Brein from Stackoverflow)*	original dataframe with UTM zone, Northning and Easting columns added
STC_Geocentre&Dis tance & Interaction Calculator.R	*geocentrecalcPt1()*	two points with lat\long coordinates	Together the two functions calculate the geo central or mid point for two or more given points	half of the calculation (input for geocentrecalcPt2())
	geocentrecalcPt2()	geocentrecalcPt1() output		a geocentric midpoint
	Distance_Outlier_C alculator()	dataframe* and time period (t1 & t2)	retrieve possible outliers from the dataset using the rdist.earth function that calculates the distance between two points over the earth (a threshold distance value is used to determine possible outliers (x > n = outlier)) generally uses the population averaged track points for comparative points	a subset of the original dataframe of all possible outliers (distance to nearest individual column included)
	Distance_Interactio n_Calculator()	dataframe* and time period (t1 & t2)	retrieve possible interactions from the dataset using the rdist.earth function that calculates the distance between two points over the earth (a threshold distance value is used to determine possible interactions (x < n = interaction)) generally calcuated between all points	a subset of the original dataframe of all possible interactions (distance to nearest individual column included)
STC_Dataframe&Lin es List Maker By Individual.R	*STC_Individuals_Dat aframe_List_Maker ()*	dataframe*	Creates a list of dataframes where each dataframe holds the data of a separate individual (for individual specific analyses)	list of all individual dataframes
	STC_Individuals_Lin es_List_Maker()	dataframe*	Creates a list of lines where each line holds the data of a separate individual (for the creation of sp lines object)	list of all individual lines in sp format
STC_KDE_Calculator .R	*STC_KDE_Calculator ()*	dataframe*	Calculate a multidimensional KDE estimate of home range for a specified dataframe in both time and space	a multidimensional space-time KDE of the given dataframe
STC_Base_Map_Gen erator and Visualizer Functions.R	*STC_Base_Map_Ge nerator()*	dataframe*	Retrieve a base map using the OpenStreetMap package	a basemap of the specified location
	STC_Base_Map_3d _Visualizer()	basemap	adds a z value to an OSM map for visualization *(All thanks and rights for the original script "map3d" go to StackOverLoader (Spacedman))*	a basemap with z values added

Table 6: STC R Code Guide Part 2 (visualization)

Script	Function	Input	Process	Output
STC_Internal_Visualizer Functions.R . (STC Visualization Functions based on the RGL package and others specifically for internal analysis of the STC on the R platform)	*STC_2D_Background_Visualization()*	dataframe* and basemap	add a 2D visualization of the data on a base map to the scene	basemap with points oor lines etc visualized in the scene
	STC_Internal_Visualization_Setup()	dataframe*	STC visualization setup using plot3d (creation of the basic bounding box and axes)	empty STC with axes and labels
	STC_Internal_Point_Line_Sphere_Visualizer()	dataframe* and visualization option (either 'point' | 'line' | 'sphere' | 'tetra' for tetrahedron | 'cube' | 'sprite	visualization of points,lines or spheres using plot3d	visualization of the specified objects within the current scene
	STC_Internal_KDE_Visualizer()	STC_KDE_Calculator() output or KDE estimate	visualization of three dimensional KDE home ranges using plot3d	visualization of the specified KDE within the current scene
	STC_Identify3d()	none	select points of interest from within a visualized scene (click on points in a scene and retrieve their identifiying code and visualize specified info in the scene)	specified information about selected points added to the scene next to points and a vector of identifier codes for the selected points created
	STC_Point_Retriever()	dataframe* and point identifier codes or STC_Identify3d() output	retrieve selected points of interest from within a dataset based on their location from STC_identify3d() or general knowledge of their identifying code	a subset of the input dataframe based of given identifier codes
	STC_add_point_info()	point identifier codes or STC_Point_Retriever() output or Sequence_Date_points() output	add point info to the current scene next to specified points (follows Sequence of date points gnerally)	specified information about selected points added to the scene based on the dataframe subset
	STC_Static_Titles()	title and subtitle	add static titles and a 2D visualization to the scene	static title and subtitle added to the scene
	Sequence_Date_points()	dataframe* and a time interval	create subset of datapoints based on time intervals so as to provide date info in the visualization (alternative to having date as the z axis)	a subset of the input dataframe based oftime intervals
Notes:	*dataframe required works best if it matches the format of the dataframe produced by STC_Movebank_CSVtoDF() only neccescary inputs are listed (secondary options LL or UTM input, colour or font etc can be found within the script)			

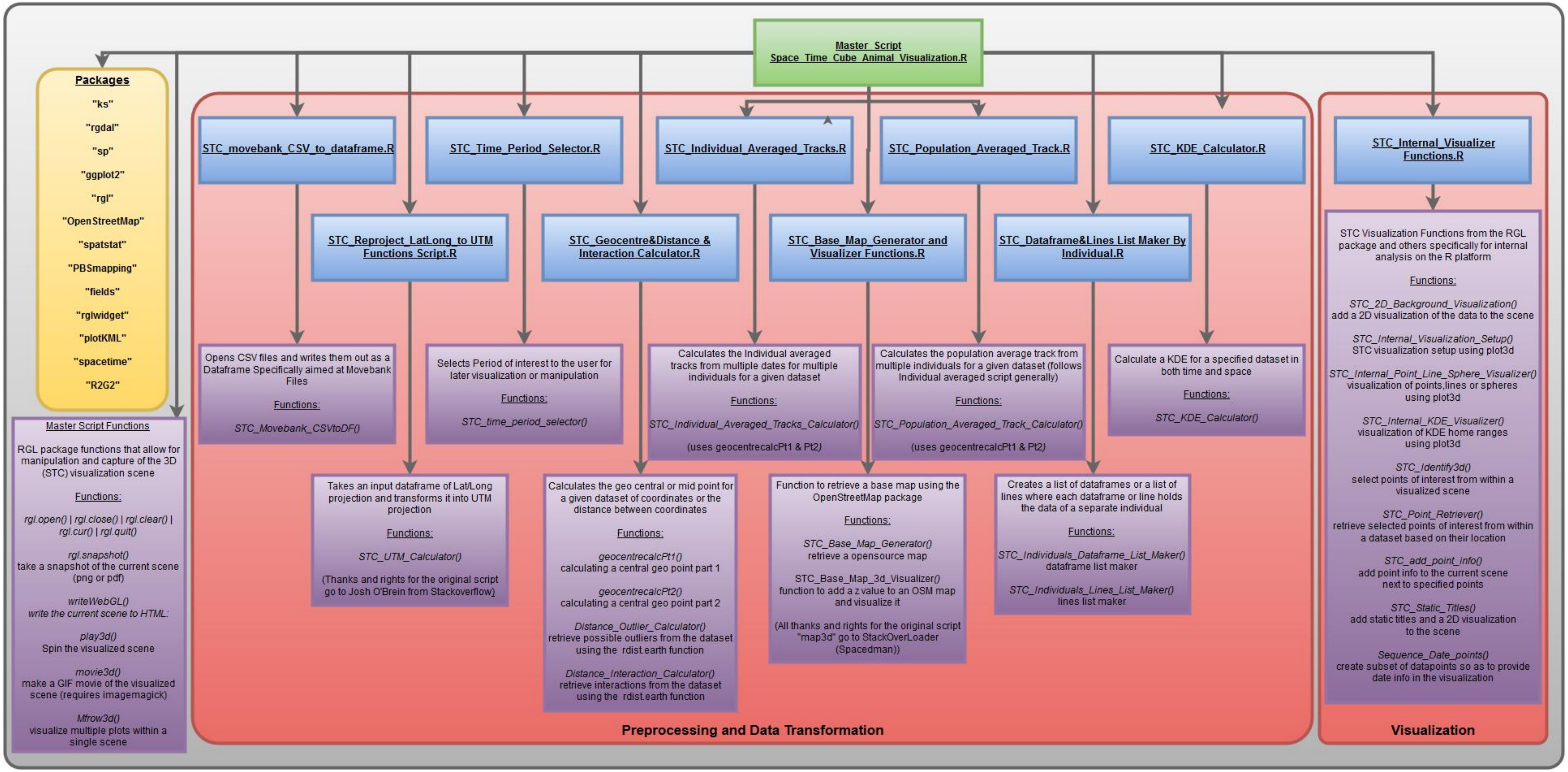

Figure 24: Diagram of the STC R code setup and relationships