From Map to Sky: an Empirical Study on Visual Strategies of Expert Pilots

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Abstract. For pilots, making the right choice of waypoints on an aeronautical chart for navigation is a complex cognitive task. This task involves the pilot's ability to match the geographical objects depicted on the maps with the mental representation of the corresponding physical objects, actually present in the natural environment. Our objective is to investigate the mental strategies, which are underlying expert pilots' waypoints selection and to model them for training. This article presents a first modeling step, based on an empirical study using eye-tracking methodologies, combined with other experimental techniques.

Keywords. Visual attention, matching, cartographic and mental representation, mental simulation, eye-tracking, aeronautical charts.

1. Introduction

This paper presents a study in the domain of geovisualization applied to aviation training. The study is part of an ongoing multidisciplinary research project, linking Geographic Information Sciences, Computer Sciences and Human Factors, which investigates the activity of flight training, both in preparation and in flight. The project aims to design assistance tools, based on behavioral diagnosis, which would be able to assist the flight instructor monitoring the activity of the student pilot. For instance, by tracking eye-gazes, the flight instructor can verify that the student pilot performs complex procedures as scanning instruments or using aeronautical charts.

The study presented in this paper analyzes an essential activity in learning to fly: the reading and processing of geographic information depicted, in different formats, in the flight preparation environment. It focuses on a complex cognitive task that is making the right choice of waypoints on an aeronautical chart for navigation. In learning to fly, the choice of the way-
points is not easy for novice pilots: choosing a wrong landmark, that is to say, to define a landmark that is barely visible in the real environment, can lead the novice pilot to get lost. In this situation, a support tool should be able to diagnose a poor choice and possibly alert the flight instructor of the mistake made by the novice pilot during navigation preparation.

Our study uses behavioral diagnosis based on the recognition of activity and on the modeling of expert knowledge (Wenger 1987). This paper presents the exploratory process that we used to model the right choice of waypoints on the basis of visual strategies of experts pilots, and the experimental design that allows the validation of (or a part of) the conceptual model.

2. Background and General Questions

The attention of an airplane pilot is made up of several dimensions, but its main component is visual attention. The study of visual attention can be carried out with eye-tracking techniques which consist in recording human eye movements (Ware 2008). Eye tracking studies for cartographic stimuli range back to the 1970s and 1980s. Recent work in GIScience research with eye-tracking has focused on usability aspects of interactive maps, such as effectiveness and efficiency of different map designs (Çöltekin et al. 2010) or for spatial decision making and way-finding in the lab (Keifer et al. 2014). Eye tracking also enables researchers to enhance cognitive models that describe and predict how humans behave in, and reason about space (Keifer et al. 2017). Overall, this study falls within the theoretical and methodological frameworks of research in geovisualization and human factors (Montello 2002) and is based on the approaches to the study of expertise (Ericsson et al. 2006).

Our study aims to identify and model the expert knowledge mobilized when operating a flight under “Visual Flying Rules (VFR)”, that is when the pilot is able to fly the aircraft with visual reference to the ground. In particular, our study focuses on a task that is essential to operate a VFR flight: the choice of the navigation waypoints. A waypoint is a landmark, which allows the pilot to validate the direction of his/her flight. The pilot marks it on the map manually during the preparation in order to recognize it once in flight. From a cognitive point of view, the waypoint implies the matching between the geographical objects depicted on the map and the mental representation of the corresponding physical objects actually present in the environment. For this, and based on our exploratory approach, two fundamental research questions, related to the study of visual attention, have emerged:

1. What information on the paper map (map objects) do the pilots select as the landmark (ground objects) in the real environment?
2. What are the salient parameters that characterize these map objects?
3. **Methodology**

To answer these questions, a three steps experimental approach was used:

1. **Collection of expert knowledge.** A qualitative approach, based on the analysis of interviews with expert pilots, supported by the outcomes from the state of art, and in particular by the works of the US Federal Aviation Administration (Chandra and Hannon 2000), made it possible to draw up a list of cartographic objects used as potentially suitable waypoints (cities, villages, lakes, rivers, railways, highways, ...).

2. **Elicitation of the model.** The features of these waypoints were modeled for the standard the OACI-VFR 1: 500000 France metropolitan aeronautical map\(^1\). The model is based on the Saliency Vector Model (Caduff and Timps 2008), the Landmark-based Pedestrian Navigation Data Model (Fang 2012) and on the spatial relations rules applied in common GIS (ArcGIS, QGIS). It allows to describe each suitable waypoint by a contextual salience that is the combination of the characteristics of visual-perceptual salience (i.e. shape, color, dimensions, ...), semantic salience (i.e. type, role, ...) and structural salience (i.e. topological rules and relative locations), as well as a cognitive salience (i.e. mental representation). Figure 1 shows a simplified scheme of the conceptual model.

![Figure 1](https://www.geoportail.gouv.fr/donnees/carte-oaci-vfr)

**Figure 1.** A simplified scheme of the conceptual model. In *italic* features that are not yet treated in the study.

3. **Evaluation of the model.** The main features of the model were tested with an evaluation protocol, based on a triangular approach, combining vision-speech-activity tracks (HolmQvist et al. 2011). In a cognitive process this corresponds respectively to (a) the acquisition of the cartographic information by the visual attention, analyzed with eye-tracking methods, (b) the conceptualization and explanation of information,

\(^1\) [https://www.geoportail.gouv.fr/donnees/carte-oaci-vfr](https://www.geoportail.gouv.fr/donnees/carte-oaci-vfr)
processed with verbal data analysis methods and (c) the operationalization of information through decision-making and the marking of the waypoints on the map, analyzed with the description of the tracks.

This paper essentially presents the evaluation phase related to the analysis of visual attention.

4. **Eye-Tracking Experimental Setup**

Given the numerous combinations of salience characteristics that the model can describe, we have chosen to evaluate a reduced part, defined hereafter in the experimental hypotheses, of which we present a synthesis.

**Hypotheses:** landmarks are chosen if they are not ambiguous and differentiate themselves from the neighborhood by the following topological rules:
- **H1a:** for objects with surface geometry (city, villages, lakes, ...) there are no types of the same feature class (*within a given distance*).
- **H1b:** for objects with surface geometry, there are types with the same features, but with different dimensions (*near*).
- **H2a:** for objects with linear geometry (river, railway, highway, ...) they traverse another type or another feature class (*intersection*).
- **H2b:** for objects with linear geometry, they touch the boundaries of another type or another feature class (*boundary touches*).

**Participants:** seven flight instructors from a flying club (including two former military instructors). One woman and six men, aged between 45 and 82 years. All have more than 500 flight hours.

**Tasks:** Participants were asked to realize two tasks. The first one consists of preparing two imposed navigations (routes) on the OACI-VFR map, manually marking 5 waypoints for route R1 and 10 for route R2, while wearing eye-tracking glasses. The second task is a recorded interview: participants were asked to give explanations about the reasons for their choices.

**Equipment:** Tobii Glasses2 mobile eye-tracker with Tobii Pro Lab software, excerpts from OACI-VFR map, materials for drawing (ruler, pencil, gums).

**Metrics for eye-tracking:** total fixation number, fixation duration, dwell number and time to 1st fixation (Holmqvist et al. 2011).

**Analysis techniques:** heat maps and AOIs with descriptive statistics.

5. **Preliminary Results**

Preliminary results from gaze data analyses (and supported by semantic analysis of verbal data) show that pilots choose nearly the same waypoints
locations for their routes, and that the waypoints characteristics meet the criteria set out in the model assumptions. This is particularly evident for structural saliency parameters, as topological rules of ‘intersection’, ‘near’ and ‘within a distance’ seem to govern pilots’ choices. Figure 2 shows the merged heat map of the selected waypoints in route R1 for all participants and the occurrences of topological rules in their choices.

Figure 2. Heat map of the selected waypoints in R1 and occurrences of topological rules.

Eye-tracking analysis provided a deeper understanding of all the areas explored by the participants. Indeed, pilots explore, along their route, other areas containing landmarks that could meet the criteria of the assumptions, but they are not selected for navigational setup purposes. Gaze data analysis with AOIs statistics for time to 1st fixation, shows that AOIs including selected waypoints appear to be visited first, on each section of the route, as Figure 3 illustrates for one participant. This sequence of visits represents an “expert” approach and it could be comparable to novice approaches.

Figure 3. A schematic representation of the sequence of visual visits among waypoints AOI (pink) and other areas AOI (blue) of the route (R1) for one pilot.
6. Conclusion

This preliminary study enabled us to identify, mainly qualitatively, the strategies of choice of suitable waypoints for expert pilots. The eye-tracking approach was key to finely understanding the experts’ strategies of visual search and his/her decision-making. Nevertheless, other approaches, including observations in real flight conditions as well as analysis on cognitive strategies expert vs novice, must be put into perspective in order to complete the theoretical model. Moreover, a simplified version of the theoretical model was implemented as a “proof of concept” in a GIS to evaluate the automatic identification of suitable waypoints.

This work has been supported by national grants ANR-11-EQPX-0002 and LIG Emergence 2016 AIRBORNE.

References


