Assessing and improving 3D rotation transition in dense visualizations

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When visually exploring a multidimensional dataset with a 2D visualization (e.g. scatterplots), users may switch views with a smooth 3D rotation. We identified three expected benefits of such transitions: tracking graphical marks, understanding their relative arrangements, and perceiving structural elements. We studied existing implementations of progressive 3D rotation and found problems that prevent those benefits when dealing with dense scenes. To address this issue, we propose an improvement by wisely placing the rotation axis. We performed two controlled experiments, which confirm the expected benefits and validate our improvements to the technique. Based on these experiment results, we describe a set of interaction techniques to control the rotation axis placement and apply them to the exploration of aircraft data.

Keywords. Visual exploration, Information Visualization, Animated transitions.

1. INTRODUCTION

When visually exploring a multidimensional dataset with a 2D visualization (e.g. scatterplots), users may need to use different points of view in order to discover information. One way to perform a smooth transition between two points of view is to use a temporary 3D view that rotates like a transparent dice (Elmqvist 2008; Hurter 2009; Bezerianos 2010;). The assumed benefit of the technique is that the rotation and the accompanying changing visual structure are supposedly easier to understand since they are ecological (Fitzmaurice 2008) i.e. humans, as living organisms, have evolved and tuned their perceptual systems to perceive occurring events in nature, such as rotations (a rolling boulder, a fruit or a tool in a hand, etc.). As a transition technique, 3D rotation in information visualization has not been explored sufficiently to understand the very features that make it succeed or fail as a transition aid. Furthermore, in previous works, the scenes that illustrate its use were relatively scarce, and involved small graphical marks (Elmqvist 2008; Bezerianos 2010;). In these conditions, 3D rotation seems to succeed, but other situations do exist where the number of graphical marks is large enough to prevent the user from understanding the transition, despite the rotation technique. For instance, data visualized by Air Traffic Control analysts can contain a large amount of entries (up to 20,000 trajectories, Figure 1). In such overcrowded visualizations, tracking a specific trajectory during transition is harder, notably because of the plot density i.e. the noise effect created by other trajectories (Figure 1). In this case, what are the expected benefits of 3D rotation as a progressive transition? How effective is 3D rotation in those dense scenes? Does the rotation really enable users to understand the relative arrangements between graphical marks and the relationships between data?

In this paper, we investigate the perception of 3D rotation, in order to understand, improve and assess its effectiveness in information visualization tasks. In particular, we experimentally assessed whether 3D rotation only (i.e. with no other depth cues than parallax motion) helps:

- track objects during view changes,
- perceive and understand the relative arrangement of graphical marks,
- perceive structural invariants (i.e. noticeable spatial arrangement).

As an improvement of the transition technique, we also propose and experimentally assessed whether using a Focus-Centered rotation is better than a Non-Focus-Centered rotation. In light of these results, we present an interaction technique that enables users to define the axis of rotation.

2. RELATED WORK

2.1 Progressive 2D and 3D transition in HCI

Boyandin et al. (Boyandin 2012) showed that participants performed better with animation when finding geographical changes rather than with small-multiple views. Moreover, using small multiple views tends to shrink the surface required for each single view, which hinders perception in

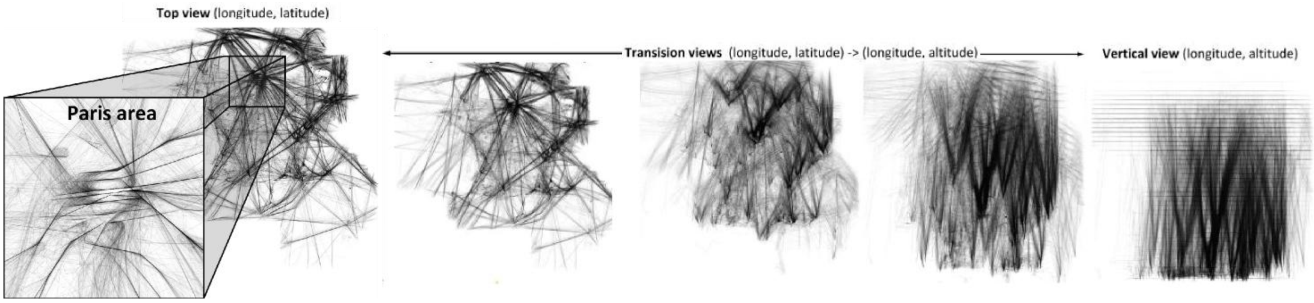


***Figure** 1*: *3D transition between the Top view (longitude, latitude) and the Vertical view (longitude, altitude*)

dense scenes and is not suitable when showing very dense views. However, Tversky et al. (Tversky 2002) showed that certain animated transitions is not better to depict view changes than displaying static images. Yet, Tversky et al. suggest that animated transitions can be suitable for real time reorientation in time and space Bederson & Boltman added a one-second transition animation to a hierarchical family tree organization and compared this to a non-animated version of the identical tree on navigation, memory and tree reconstruction and satisfaction measures (Bederson and Boltman). They found that rotation effectively helps understanding structures, but there is no detailed analysis on how users pick up information from the transition. Schlienger et al. studied the use of animation to help users understand rank changes of graphical items in a vertical list (Schlienger 2007). The experiments show that animations not only enable users to perceive that a change occurs, but also that users are able to pick up information through static parameters of animation. Heer & Robertson ran experiments about the effectiveness of various animation types in object tracking and value change estimation (Heer 2007). All animations use a 2D interpolation between an initial position and a final position. They found that the number of objects hindered effectiveness. Staging animation is slightly but statistically better than other types of animation. The authors suggest that this may be due to minimized occlusion between moving marks during interpolation. Shanmgasundaram & al. also demonstrated how animation makes users more efficient in graph and tree understanding (Shanmugasundaram 2007), and in Zoomable User Interfaces (Shanmugasundaram 2008). Cone trees relied on the visual perceptual tracking system, allowing the user to pre-attentively perceive change as a single structure undergoing transformation (Robertson 1991). While a simple demonstration comparing the transformation with and without animation shows the effectiveness of the technique, no user studies were done to verify it. Furthermore, there is no detail on how animation is supposed to help understand the visual structure. Robertson & al. used pivot rotation to help users understanding polyarchy (Robertson 2002). They tested the ability of participants to answer semantic questions about polyarchy. They found that animated transitions perform better than simply switching between views. However, the rotation only helps users track a single identified item (the pivot item).

2.2 3D Rotation

ScatterDice (Elmqvist 2008) uses a 2D projection of a 3D rotation between two scatter plots. According to their authors, “this gives some semantic meaning to the movement of the points, allowing the human mind to interpret the motion as shape”. However, there was no intent from the authors to clarify the benefit of “interpreting the motion as a shape” (Ullman 1979), to understand it, or to verify experimentally that it was effective. GraphDice uses a similar technique to explore graphs (Bezerianos 2010). Similarly, the authors rely on the “extraction of structure from motion”, but they do not attempt to assess it. With GraphDice and ScatterDice, when the user zooms in, the software automatically zooms in on the selected data, before the rotation occurs. Thus, the user does not lose the focus zone. In this case, only the selected data rotate (due to the initial zoom) and all visual entities remain visible. However, the “context”, i.e. the surrounding marks, is lost. In (Sanftmann 2012) Sanftmann showed that users performed significantly better with a 3D rotation with multiple depth cues than with a direct interpolation between views for tracking clusters between 3D scatterplots. However, the study did not deal with relative arrangement of objects, nor noticeable spatial arrangements and nor the discovery of particular shapes in dense scatterplots. The authors of Safe 3D navigation referred to the problem often encountered by users that a rotation may lead to a camera pointing to an empty space (objects are disappearing) (Fitzmaurice 2008). They proposed a set of properties amenable to safe 3D navigation, but the properties are targeted at navigating in the 3D model, and do not take into consideration the goals pertaining to visualization of information.

3. EXPECTED BENEFITS OF 3D ROTATION

Designers of 3D rotation transitions obviously expect benefits of such technique. The benefits for visualization (e.g. to understand and detect information from a dataset) are specific, and are not the same as other activities, e.g. 3D modeling, as those activities do not deal with data exploration. However, we could not find in previous works a clear description of the exact phenomena that are supposed to be at work when exploring visualization. In the following, we suggest three expected benefits and the problems that may prevent them from occurring.

3.1 Expected benefits

We think that 3D rotation helps visualization tasks in at least three ways: (1) keeping track, (2) perceiving relative arrangement, and (3) perceiving structural elements. First, it helps viewers to keep track of a particular graphical mark, and its final location in the final view of the transition. For example, one can try to track the trajectory of the AF453 aircraft in the top view to see how its flight level evolves in the vertical view by following the line while it moves during the animated transition. Though it was not clearly stated in previous works on 3D rotation, this benefit is shared by all transition techniques, including 2D ones. However, during a 2D transition with simultaneous movement of marks, marks are moving in a completely unrelated manner, which may make the perception of individual marks difficult. On the other hand, 3D rotation makes movement of marks more predictable, hence easier to track individually.

A second expected benefit is that 3D rotation animation should enable users to rank marks by their proximity, guess their distance, and more generally understand the spatial relationships between marks i.e. the relative arrangement of marks. Finally, a third 3D rotation animation benefit is to help users perceive structural elements in a noisy scene: when the rotation occurs, the relative movement of marks may exhibit those regularities e.g. common fate, or reveal a rigid structure e.g. alignment that holds true during the rotation (all the graphical marks belonging to the same plane move the same way during transition). Those regularities can be picked up by the visual perceptual system thanks to the rotation animation, which gives additional information on the data that would be unnoticed through the static representation. Perceiving the relative arrangement of marks (second expected benefit) relies on correct tracking of marks (first expected benefit). Similarly, perceiving structural elements (third expected benefit) relies on the correct perception of relative arrangement (second expected benefit). This is the reason why we assessed those expected benefits in order and incrementally: if one cannot track elements, one cannot perceive arrangement or structure.

3.2 What does or may prevent benefits?

3.2.1. Depth Perception

If occlusion and parallax motion are not properly managed, users cannot perceive depth of visual marks. Braunstein et al. found that occlusion of more distant texture elements by nearer elements was sufficient for the perception of direction of rotation for displays that included static as well as kinetic occlusion (Braunstein 1982). Furthermore, depth order from purely kinetic occlusion can be used to resolve ambiguity of the direction of rotation in parallel projections (Andersen 1983) (Braunstein 1982). Rogers and Graham found that parallax motion alone can provide the impression of depth (Rogers 1979). Interestingly, the experiment displays shapes by using a transparent surface texture with spare dots, which resembled the graphics used in ScatterDice. Participants were able to give accurate information on the shapes, though the only depth cue was parallax motion.

3.2.2. Density and Clutter

Numerous papers illustrate the use of transition with examples that manipulate a few dozen graphical marks (Elmqvist 2008; Bezerianos 2010). In this situation, 3D rotations “work”, particularly when tracking a particular mark. Braunstein found that the number of dots has a positive effect on the perception of depth in rotating dots patterns (Braunstein 1984). However, the experiment involves only dots, and we do not know if this result holds true with more complex shapes. Furthermore, the experiment did not consist of following a particular dot, but rather whether the display gives the impression of depth. Petersik found that the perception of depth in a dot-sampled sphere is hindered by noise in the form of randomly moving dots (Petersik 1979). However, the general perception of the rotating sphere is maintained, despite the noise. Note that this notion of noise is different from ours, which is “noise due to density”. In (Ellis 2007) Animation for Information Visualization is said to satisfy the “avoids overlap” criterion to reduce clutter in visualizations. However, with dense and cluttered views, the path of individual marks during the transition tangles with other ones. Even if the animation can be understood globally as a rotation, a single mark is harder to track and the relative arrangement harder to perceive. Further, if users are not able to grasp, recognize and understand the animation, they may have more difficulties at tracking marks, perceiving arrangement and perceiving structural elements. Visualization software to explore aircraft trajectories displays multi-segment lines instead of small dots and users can configure objects as opaque as well as translucent. When opaque objects tangle, incorrect occlusion prevents users from recognizing the animation as a rotation, and makes it difficult to track a particular item or perceive an arrangement. This flaw is not immediately noticeable since the system displays large quantities of data. However, when the user zooms in on the dataset to get details, the visualization displays less graphical marks, which makes this flaw noticeable.

3.2.3. Disappearance

In order to cope with numerous data and spoiled views, users are encouraged to zoom in and navigate on a particular part of the view. For example, users visualizing one-day of traffic over France (up to 20 000 displayed trajectories) and needing a more precise point of view over Roissy-Charles De Gaulle zoom in on the Paris area to analyze landing and taking-off aircraft from a top point of view (i.e. X screen axis mapped to latitude, Y screen axis mapped to longitude). Once they filter these trajectories, they want to analyze their vertical profile, i.e. visualize trajectories with a view set as X screen axis mapped to latitude and Y screen axis mapped to altitude. During an animated rotation in a zoomed view, the zone of focus may disappear since the rotation operates with the centre of the screen as the rotation centre. Consequently, users lose focus on trajectories they are studying and are not able to properly complete their task.

4. IMPROVING 3D ROTATION PERCEPTION

We have seen that 3D rotation is supposed to help users in three tasks: tracking graphical objects, perceiving their relative arrangements, and perceiving structural elements. We have also seen that in existing systems, 3D rotation transition is not efficient at supporting tracking and understanding relationships of graphical marks in zoomed-in visualization with high level of noise. We identified that the problems come from occlusion, density, and disappearance of graphical objects. We propose to improve rotation perception by using two features: correct occlusion and Focus-Centered rotation. From these observations, we propose to extend the Focus-Centered technique to improve perception of structural elements.

4.1 Correct occlusion

A solution to circumvent occlusion problems is to make occlusion hardly noticeable by using fast animations (<1s) (Elmqvist 2008; Bezerianos 2010) and small transparent graphical objects. In this case, interpreting the animation as a rotation relies on parallax motion only, which may prove insufficient for perceiving the arrangements of objects. Hence, we implemented occlusion using a Z-buffer algorithm that draws overlapping three-dimensional graphical objects correctly. Similarly to (Sanftmann 2012), we found that correct occlusion rendering has an important impact on depth perception.

4.2 Focus-Centered Rotation

Previous visualization software (Bezerianos 2010; Elmqvist 2008; Hurter 2009) use a rotation whose axis is the centre of the data set. As stated previously, users need to zoom to get detailed views. In a zoomed view, the focused visual entity (e.g. a specific aircraft trajectory) may exit the screen when 3D rotation transition occurs. Furthermore, since the axis of rotation is far, the graphical marks, including the ones that users focus on, move similarly and at a fast pace, which prevents users tracking the graphical marks of focus. To prevent this effect, a solution is to place the rotation axis so that it goes through the zone containing the focused marks. By defining this new rotation axis, the modified animation will maintain the focus zone at a relatively stationary location on the screen, thereby decreasing the cluttering effect. The world transformation matrix required is given by: $\mathbf{M_{World} = M_{Trans}(P_f) \times M_{Rot} \times M_{Trans}(-P_f)}$, with $\mathbf{P_f}$ the location of the focus point, $\mathbf{M_{World}}$ the world matrix, $\mathbf{M_{Trans}}$ a translation matrix and $\mathbf{M_{Rot}}$ a rotation matrix. By enabling again users to track marks, we expect that this will improve their ability at perceiving the relative arrangement and structural elements. The goal of the following experiments is to assess this assumption. Of course, for Focus-Centered rotation to be useful, it requires that the user define such a rotation axis (especially its position on the Z axis). The end of the paper is devoted to the design of such an interaction.

5. CONTROLLED EXPERIMENTS

We designed two experiments to assess the expected benefits of 3D rotation that we propose. In this paper, we present only the experiments corresponding to the two last expected benefits: whether 3D rotation enables users to perceive the relative arrangements of graphical marks, and whether it enables users to perceive structural elements in data.

5.1 Aircraft visualization task

Participants were asked to complete tasks related to the exploration of aircraft trajectories. When two aircraft reach the safety separation distance threshold, Air Traffic Controllers detect a conflict that can be solved in two ways: a vertical resolution (making one or both aircraft change altitude), or a horizontal resolution (making one or both aircraft change horizontal direction). When analyzing past conflict resolutions, the easiest way for analysts to understand how a particular controller proceeded to resolve a conflict, is to alternate between a top (longitude->X, latitude->Y) and a vertical (longitude->X, altitude->Y) view (Top and Vertical views,). However, the challenge for analysts is to avoid mistaking the two trajectories. Hence, the task consists in tracking a specific trajectory during the transition between two views: a top view and a vertical view, with a varying amount of surrounding trajectories.

5.2 Experiment 1: Perception of relative arrangement

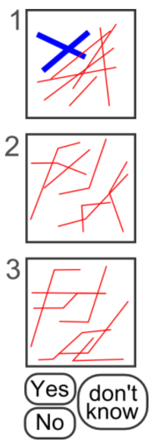
Experiment 1 investigates the perception of the relative arrangement of marks (rank marks by their proximity, guess their distance, and more generally understand the spatial relationships between marks). The goal of this experiment is to prove that, for perception of relative arrangement, a Focus-Centered rotation provides better accuracy than a Non-Focus-Centered rotation; and that Focus-Centered rotation reduces the density negative effect for perceiving relative arrangements.

5.2.1. Task

Two trajectories are displayed with polylines. One trajectory stays at the same altitude (stationary trajectory), whereas the other one changes its altitude (evolving trajectory, Figure 2, left). There are two conditions for the crossing of the trajectories: evolving trajectory above static trajectory or the opposite. The first and last frames of the 3D rotation in both conditions are not discernible. Static intermediate frames do not contain depth cues.(Figure 2, right) Only the dynamic sequence of frames gives a depth cue (relative arrangement, here parallax motion). The participant has to figure out if the stationary trajectory goes under or above the other one. This task requires the user to keep focus on the trajectories of interest among other trajectories, and to perceive the relative arrangement of the lines.

5.2.2. Procedure, experimental conditions and participants

For each trial, the order of operation was:



- The participant saw a top view with two highlighted crossing trajectories in blue; the surrounding trajectories were in red (panel 1, the thick blue trajectories).
- Three sounds were produced to warn the participant that the transition was about to start.
- The color of the specific trajectories was turned to red, so that they were no longer differentiated from the surrounding ones. The transition from the top view to the vertical one occurred (panel 2).
- At the end of the rotation, the user had to answer the question: “Does the stationary trajectory go under the trajectory that changes altitude?” The user could answer “yes”, “no” or “I don’t know” by using the keyboard (panel 3). “I don’t know” answer type was used to avoid false positive answers, and was therefore a filter to optimize the quality of correct answers.

We used 3 different density levels (empty, medium with 20 trajectories, high with 40 trajectories). Though a number of 40 trajectories are far from a typical actual scene (usually thousands), it is close to the number of trajectories in a zoomed view. There were 2 types of transitions (Non-Focus-Centered and Focused-centered rotation). To avoid the learning effect, we used 2 profiles of conflicting trajectories and 4 trajectory locations (lop-left, top-right, bottom-left and bottom-right). Participants performed 48 trials each. As participants could not give their responses before the transitions were fully played, we did not measure reaction times. The screen was a standard 21” LCD screen with a 1920x1200 resolution. We used a line thickness of 2 pixels to display trajectories. There were 11 participants, all regular computer users (researchers and PhD students in computer science, ergonomics, air traffic controllers), with an age ranging from 22 to 55 (average age of 40). Even if the task was related to a specific activity, it did not require Air Traffic Control skills. The keys to press were “a” for “no”, “q” for “yes”, and “space” for “I don’t know”. On a French keyboard, the “a” key is just above the “q” key. Hence, answering the question was equivalent to “placing” the stationary trajectory “above” or “below” on the keyboard. When asked after the experiment, no participant reported any difficulties. Since we knew the position and the shape of the two trajectories of interest, we pre-set the position of the Focus-Centered rotation axis by finding the median axis of the box that binds the trajectories. We eliminated any depth cues in particular occlusion by using opaque marks of the same color. Otherwise, participants would have been able to answer the question by using the (static) initial or final image only, which is irrelevant. The resulting animation was composed of successive frames that, if observed individually (thus statically), contained no visual depth cues.

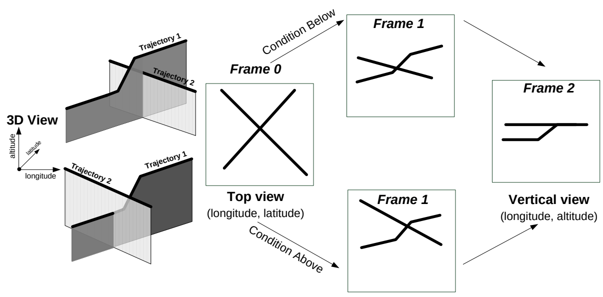


***Figure 2** : Schematics of two conditions of trajectories (left) and two sequences of frames during exp 1 as seen by participants (right). Only the dynamic sequence of frames gives a depth cue (relative arrangement).*

5.2.3. Hypotheses

Our hypotheses were (H1) Focus-Centered rotation allows a better accuracy regarding the perception of relative arrangements than Non-Focus-Centered rotation; (H2) the density level has a negative impact on accuracy; (H3) the density level has a significant deleterious impact on accuracy in the Non-

Focus-Centered rotation a much lower impact in the Focus-Centered rotation condition.

5.2.4. Results

All behavioral data were analyzed with Statistica 7.1 (StatSoft©). The Kolmogorov-Smirnov goodness-of-fit test has been used for testing normality of our variable distributions. As the latter were not normal, we used non-parametric Friedman's ANOVA and Wilcoxon Signed-rank tests (paired comparisons) to examine the effects of the type of focus and density levels on accuracy. In order to examine the main effects of focus and density level with the nonparametric analyses, we computed averaged values from raw data.

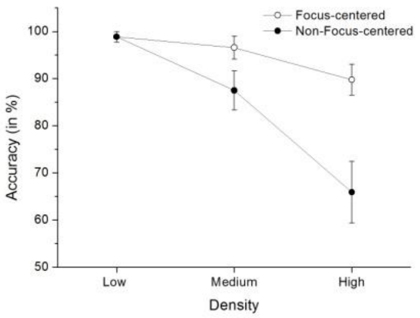


***Figure 3**: Experiment 1, percentage of successful trials with Focus-Centered and Non-Focus-Centered rotation type as a function of context density.*

The Wilcoxon signed-rank tests revealed that the Focus-Centered rotation allowed a significant better accuracy than Non-Focus-Centered rotation ($Z = 2.21$, $p = .026$). In addition, the Friedman's test showed that the density level had an overall significant negative impact on accuracy ($\chi^2(11) = 18.864$, $p < .001$). More precisely, the accuracy was higher in the low-density condition than in the medium density condition ($Z = 2.36$, $p = .017$) and higher in the medium density condition than in the high-density condition ($Z = 2.80$, $p = .005$). We then examined the density level in each focus condition. As expected, while the Friedman's test showed that the density level had a significant impact on accuracy in the Non-Focus-Centered rotation condition ($\chi^2(11) = 15.942$, $p < .001$), the effect of density did not reach the significance threshold in the Focus-Centered rotation condition ($\chi^2(11) = 5.478$, $p = .064$). It confirmed that the density had a much lower impact in the Focus-Centered rotation condition. Regarding the Non-Focus-Centered rotation condition only, the Wilcoxon signed-rank tests showed that the accuracy was higher in the low density condition than in the medium density condition ($Z = 2.36$, $p = .017$) and higher in the medium density condition than in the high density condition ($Z = 2.80$, $p = .005$), Figure 3.

5.2.5. Conclusion

Our results showed that the Focus-Centered rotation improved users' perception of relative arrangements (H1). We also found that a higher density level negatively impacted users' accuracy (H2). Furthermore, we showed that the impact of the context density is lower in the Focus-Centered rotation in comparison with the Non-Focus-Centered rotation (H3). Since participants were able to perceive the relative arrangements of the marks (H1), this also implies that users were able to track graphical marks.

5.3 Experiment 2: Perceiving structural elements

In the following experiment, we asked participants to recognize a pattern in a rotating cube, with three different rotation axes and different density levels. The pattern used was a degraded uppercase letter composed of points (Figure 4). The letter is chosen randomly among the alphabet at each test. This letter is drawn on the vertical centre plane of the cube (Figure 4). Noise density is rendered by displaying random points in the cube in order to hinder the perception of the structural element. The aim of this experiment is to assess that placing the rotation axis at the centre of the plane where the pattern is drawn improves users' perception of structural elements in cluttered scenes.

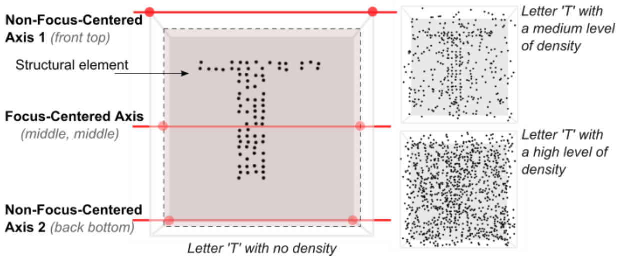


***Figure 4:** Design of the 3D rotating cube for the second experiment, with axes and different levels of density*

5.3.1. Procedure, experimental conditions, apparatus and participants

For each trial, the order of operation was:

- The display showed a rotating cube around an angle varying from PI/8 to –PI/8 with a specific axis and a specific level of density. On the central plane of the cube, a degraded letter made of dots similar to density dots was drawn.
- An animation rotated back and forth the scene for 1.5 seconds.
- At the end of the animation, the display turned black and participants were asked to type the letter they perceived in the appropriate text zone. If they did not recognize the letter, they entered a letter they thought was closest to the shape they saw.

They validated their answer by pressing the Return key. There were three levels of density: low (1000 points, D1), medium (1200 points, D2) and high (1400 points, D3). Three axis of rotation were used: the optimal axis for 3D rotation that passed through the centre of two opposite's sides (where the pattern is drawn, the Focus-Centered Axis), the axis that passed at the top edge of the front side of the cube (Non-Focus-Centered Axis 1), and the axis that passed at the bottom edge of the rear side of the cube (Non-Focus-Centered Axis 2). Non-Focus-Centered Axis 1 and 2 locations were chosen to be far from the Focus-Centered axis. Each condition was repeated eight times, resulting in 3x3x8= 72 trials. Letters from the alphabet were randomly drawn, and each letter appeared the same number of times for each condition (72/26=2.7 times per letter). The screen was a standard 21" LCD screen with a 1920x1200 resolution. The cube was 720*720*720 pixels. Plots were depicted with a 5-pixel width. The animation lasted 1.5 seconds. There were eleven subjects, all regular computer users, with an age ranging from 24 to 57 (average age was 34).

5.3.2. Hypothesis

We assumed that (H1) the Focus-Centered Axis will improve the accuracy; (H2) the density level will have a negative impact on accuracy; (H3) density level will have a stronger deleterious impact on accuracy in the Non-Focus-Centered Axis 1 and 2 condition compared to the Focus-Centered Axis.

5.3.3. Results

The Kolmogorov-Smirnov goodness-of-fit test confirmed the normality of all the variables. Consequently, we examined the effects of the type of axis and the density levels on accuracy with a two-way 2 * 3 repeated measures ANOVA. Fisher's LSD (Least Significant Difference) post hoc test was used to examine paired comparisons.

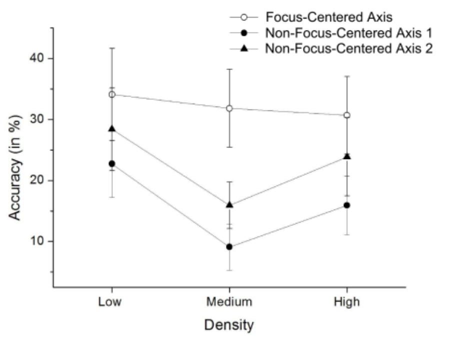


***Figure 5:** Successful trials for Focus-Centered Axis, Non-Focus-Centered Axis 1 and 2 as a function of context density*

The repeated measures ANOVA revealed a main effect of the type of rotation ($F(2, 20) = 6.91$, $p = .005$, $\eta^2 p = .40$) on accuracy (Figure 5). More precisely, the Focus-Centered Axis allowed a higher accuracy than the Non-Focus-Centered Axis 1 and 2 (respectively LSD, $p = .001$; $p = .043$). No significant difference was found between Non-Focus-Centered Axis 1 and 2 (LSD, $p = .136$). In addition, we found a main effect of the density level on accuracy ($F(2, 20) = 3.60$, $p < .046$, $\eta^2 p = .26$). The accuracy was higher in low density than in the medium density condition (LSD, $p = .014$). The mean accuracy also dropped between the low density and high density conditions, but results did not reach the statistical significance (LSD, $p = .178$). No significant difference was found between low density and high density conditions (LSD, $p = .212$). Finally, no interaction between the rotation type and the level of density was found.

5.3.4. Conclusion

Results showed that the Focus-Centered Axis achieved best accuracy for recognizing letters in comparison to the Non-Focus-Centered Axis 1 and 2, i.e. the Focus-Centered Axis provides better accuracy in perceiving structural elements (H1). Whereas we found a main effect of the density level on accuracy, and that accuracy was higher in low density than in the medium density condition, medium and high density did not differ (accuracy even slightly increased between medium and high density). The number of points to hinder the pattern in the medium and high density was certainly too close (respectively 1200 and 1400), explaining the lack of difference between medium and high density. Most likely, this issue explained the lack of interaction between axis type and density levels. Whereas the Non-Focus-Centered Axis 1 and 2 were strongly affected by the medium density level in comparison to the low density, this effect was not further increased in the high-density level. As a consequence, H3 was not validated.

6. INTERACTION DESIGN

The previous experiments showed that perception of 3D rotation is better with Focus-Centered rotation, and that perception is hindered in a cluttered scene. In the following section, we detail our implementation to perform an effective 3D rotation.

6.1 Requirements

The previous experiments helped us establish the following design requirements to perform an efficient 3D rotation transition: the system must provide interactions that enable users to place the rotation axis close to the graphical marks currently analyzed and it must reduce the impact of data density on the perception of the 3D rotation.

6.2 Interactions

A simple interaction could have consisted in drawing a line representing the axis inside the view, and in moving this line around. However, it is difficult to perceive where the line should be with respect to

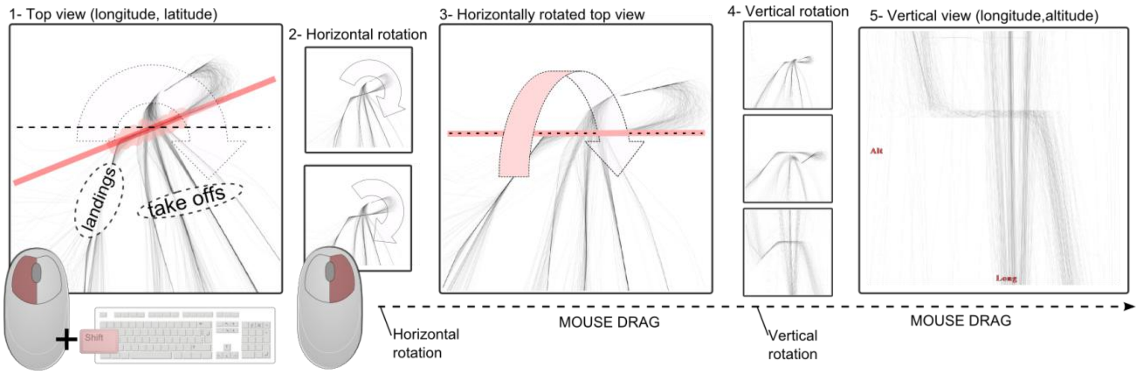


Figure 6: *Storyboard of the brushing and the controlled staged animation. In the top view (1) the user brushes the crossing trajectories (shift key + left mouse button + drag). The system computes the depth and the angle of rotation. The user controls angles of the staged transition (right button + drag): a first rotation brings the trajectories parallel to the axis of rotation (here, the X axis, Horizontal rotation, 2), second the user controls the second rotation (Vertical rotation, 4)*

the trajectories the users focus on. Hence we devised an interaction technique based on automatic calculation of an 'optimal' axis with respect to a set of trajectories that users specify.
First, users select a set of graphical marks with two possible means:

- either users set the location and the radius of a circular lens by respectively moving the mouse and rotating the mouse wheel while holding the control key: graphical marks inside this lens are selected,
- or users press the shift key on the keyboard and by dragging the mouse, they brush trajectories to select them, (Figure 6, 1).

During both interactions, users can rotate the mouse wheel to select graphical marks by their "depth". In fact, the dimension of the data corresponding to the "depth" is the dimension that will be mapped on the Y axis of the screen after the rotation e.g. in a top view displaying aircraft trajectories, the 'altitude' dimension will replace the 'latitude' one on the Y axis. The mouse wheel controls the center of a range corresponding to 10% of the total range of values. Marks whose values of this dimension fall into the range are turned to red: enabling users to browse rapidly through marks and see if the marks they focus on are near the axis. After having selected a set of graphical marks, the system computes the optimal axis. Users can then trigger the rotation of the entire scene by clicking on one of the axis of the view, or control the rotation by pressing on the X or Y axis of the view and dragging the mouse in the direction of the rotation. To compute the optimal axis, the system could have computed the barycenter of the selected data. However, in the case of aircraft trajectories, this could have resulted in a position of the axis with no trajectories around. In order to ensure that the rotation axis lies among a cluster of trajectories, we used an algorithm based on a histogram instead. For each segment of the selected trajectory, the average depth of the segment is computed and put into a histogram i.e. the number of segments with this depth is incremented. The resulting depth is the one that is shared the most by the segments of the selected trajectories.
The rotation of the entire scene can hinder the perception when the view is too dense because it includes all graphical marks. In this case, users can choose to focus a rotation in a lens. By holding the control key and using the mouse wheel to change the size of the lens, the user defines the area that will be rotated. The same histogram technique is used to compute the optimal axis. When the user triggers the animated transition, only graphical marks within the lens are rotated. The user can control the rotation within the lens using mouse drag on the X or Y axis of the view. We also noticed in the case of aircraft data that when the trajectories of focus are not parallel to the axis of rotation, it is difficult to track them. In fact, during the rotation, the two end points of a trajectory that is not parallel to the axis of rotation may come closer together. This results in a seemingly shorter trajectory becoming hard to track during the rotation. We implemented a staged animation (Heer 2007) to improve understanding of 3D rotation in this case: before the rotation occurs, the system performs a previous '2D' rotation of the selected trajectories so that they mainly have a horizontal or vertical direction. To do so, the system computes the average direction of the brushed trajectories, and then deduces the rotation angle (Figure 6, 2). Using mouse drag with right click, the user can control the two rotations of the staged transitions (Figure 6, 2, 3). The angle calculation uses a similar histogram algorithm, by computing the angle between each trajectory segment and the non-changing axis. We also adapted this staged transition technique for scatterplot visualization. The angle calculation for the first 2D rotation is given by the bounding box of the brush's maximum dimension which is to be aligned with the horizontal or vertical axis.

7. USAGE SCENARIOS

In the following, we present three usage scenarios that illustrate the benefits of using 3D rotation as a transition technique.

7.1 Scenario 1: Discovering and tracking a noticeable behavior in trajectories

The visualization system displays a dense dataset of aircraft trajectories (Figure 7, 1). The user wants to analyze the vertical view, which displays the trajectories according to their longitude and altitude. To do so, the user changes the latitude dimension for the altitude dimension; the system plays a global rotation transition with a default rotation axis (Figure 7, 2, 3). During the transition, the user perceives that a trajectory has a noticeable shape, but could not see it clearly because the scene is cluttered and the axis of rotation is not properly set. The user goes back to the initial view, the transition is played again and the user detects the position of the trajectory. Then, the user zooms in on the area where the noticeable trajectory is supposed to be, adapts the size of the lens and places it on that area (Figure 7, 4). The user changes the view to show the vertical view of the selected trajectories. The system plays the 3D transition in the lens: the trajectories in the lens rotate, while the trajectories out of the lens do not (Figure 7, 5). Thus, thanks to this transition, the user can perceive that the special trajectory depicts an "8" (this trajectory cannot be properly perceived on a static image: we highlighted the 8 to help the reader of this article perceive it in the 5th frame of Figure 7).

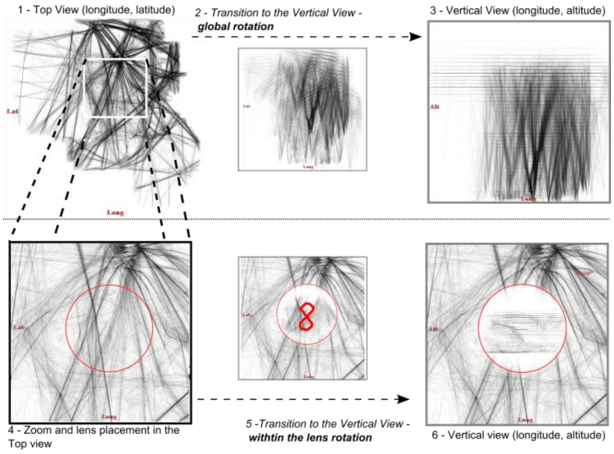


Figure 7: *.The user switches from a top (1) to a vertical (2,3) view. In the top view, the user selects graphical marks with the lens (4). During the 3D rotation within the lens, the user perceives that the noticeable trajectory depicts an "8" (5).*

7.2 Scenario 2: Analyzing takeoffs and landings

The system displays aircraft trajectories seen from the top. The user is analyzing the traffic of one day at Orly airport, and verifies the takeoff and landing procedures i.e. verifying that landing aircraft pass over aircraft taking off. Two main aircraft streams emerge: the landing aircraft stream and the stream of aircraft taking off (Figure 6, 1). None of the top or vertical views allow the user to see which stream goes above the other (Figure 6, 1, 5). Since there is no "stream" field in the data (streams only emerge in the representation), there is no possibility for the user to map a stream to a visual variable: he must rely on 3D rotation to understand the relative arrangement. The user's focus is the crossing of the landing and takeoff streams; the user brushes the crossing streams (Figure 6, 1), and switches from the top to the vertical view by changing the Y axis. A first transition is played bringing the focus trajectories parallel to the axis of rotation (Figure 6, 2, 3) and a second transition switches to the vertical view (Figure 6, 4, 5). During the second transition, the user can clearly see thanks to the perception of relative arrangement that the aircraft landing stream passes over the taking off aircraft stream. The user controls the staged transition and validates that landing aircraft do indeed pass over aircraft taking off.

7.3 Scenario 3: Application to Scatterplot visualization

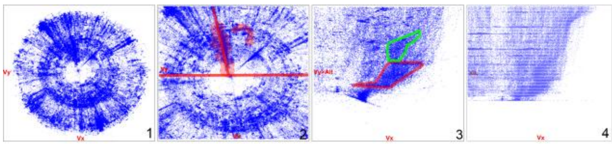


Figure 8: *A staged transition (2, 3) between aircraft Vx/Vy speeds view (1) to a speeds/altitude view (4).*

The system displays a large amount of aircraft speed data in a scatterplot visualization; the Vx component of aircraft speed is mapped to the X axis of the view, the Vy component is mapped to the Y axis of the view (Figure 8, 1). This visualization shows an outer disk corresponding to high speed aircraft and an inner disk corresponding to low speed aircraft (Figure 8, 1). Clusters emerge from this scatterplot and correspond to records with the same direction. The user brushes a cluster that corresponds to aircraft with a slow speed that are landing (Figure 8, 2). The user now wants to visualize the speed distribution in this cluster by altitude. This is done by mapping the altitude on the Y axis. Using a staged animation as in the previous scenario, the view is first rotated to the right (Figure 8, 2) in order to bring the cluster parallel to the rotation axis, and the transition showing aircraft speeds on the X axis and aircraft altitudes on the Y axis is played. The user is able to perceive two sets of trajectories that follow roughly the same path (i.e. two structures) during the 3D transition. A particular area in the intermediate image 3 (green contour added to the Figure 8, 3) contains aircraft above 160 flight level with a small speed range. Another area contains aircraft below 160 flight level with a larger speed range. The green area (>160 flight level, small speed range) corresponds to aircraft whose speed is still controlled by Air Traffic Controllers; the red area (<160 flight level) are aircraft that had be given an instruction to land and are no longer constrained by the speed previously given by the Air Traffic Controllers. This freedom left to pilots explains why the red area shows a larger range of speeds. It is important to note that this information is not visible in the final frame (Figure 8, 4), but only through 3D rotation, the perception of two clusters, and the perceived relationships between the two images. This allows the user to understand the data and discover new information i.e. the variety of speeds during the landing stage.

8. CONCLUSION

In this paper, we identified and assessed with controlled experiments that 3D rotation helps users in tracking marks (1), perceiving their relative arrangement (2), and perceiving structural elements (3). We identified three factors that may prevent benefits of 3D rotation: density, occlusion and disappearance of graphical marks. The results of the experiments also validate that density has a negative impact on users' accuracy, and that users benefit more from the transition when the rotation axis is at the center of the graphical marks they are analyzing. Finally, we proposed new interactions that enable users to correctly tune the rotation. As a contribution, this work validates for the first time, 3D rotation transition in information visualization properties (1) (2) (3), and proposes an improvement to the existing technique with new interaction paradigms.

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