algorithms are stimuli-blind. Thus, this is another place where machine learning could be integrated into the algorithm. Letting an algorithm "see" by itself is far easier than providing the complete information of every stimulus used every time.

6. CONCLUSION

Overall, the prototype system developed during this study has successfully achieved the goals of constructing an accurate and robust fixation detection method and producing realistic 3D visualizations for eye-tracking data. The system has enabled car designers and engineers to examine and analyze both the customers' and their own visual behavior, making it possible to integrate the 3D gaze data as an additional layer into the virtual modelling of the product, and visualize customers' input in a useful way. The expected outcome of this study is focused more on the inventory of the method for collecting and representing gaze data, rather than defining or studying use cases under different scenarios (e.g., driving, parking, and so forth) for future user behavior research and evaluation.

In feature evaluation of a design product, analysis in gaze fixation data are beneficial. However, the study in the 3D representation of gaze fixation data is still too little. The intent of this thesis was to construct a robust and accurate method for the identification of fixations, as well as an appropriate technique to visualize them. In this paper, a combination of I-VT and DBSCAN algorithms is proposed as the fixation identification approach, which was proven to have the optimum performance across various metrics in the pilot studies and the lateral comparisons. A modified heat map, a cluster plot, the convex hulls, and the textual information together compose the complete visualization scheme, making the solution concise and easy to use without the requirement of any prior knowledge in eye-tracking.

To implement the proposed system, a VR head-mounted display with a built-in eye tracker was used. The geometry and appearance designers could easily record, analyze, and visualize eye-tracking data with the system. Four applications of this toolset were raised within the department of perceived quality:

- Ranking the visibilities in different areas of the car.
- Making comparisons between different design releases (vertically).
- Possibly extracting generalized interaction patterns among all car models (horizontally comparison).
- Prioritizing input requirements (e.g., the gap between the car hood and the headlight).

The potential further improvements of this study are mainly in designing the fixation identification algorithm and the reliability of the visualization, as well as a comprehensive definition of use cases and corresponding evaluation method. The accuracy of the eye movement classification still needs to be studied with more in-depth research. Simultaneously, the visualization should also involve more quantitative analysis to provide reliable suggestions to the aesthetic designer as the primary consumer of such a system.

ACKNOWLEDGEMENTS

I would like to thank my supervisor Christopher Peters for all the helpful discussions and suggestions. Thanks to my supervisors at Volvo Cars, Ola Wagersten and Karin Nordvall, for creating the opportunity to conduct this study that strongly appealed to me, as well as all the guidance and help in the work-life at Volvo Cars. Thanks to Timmy Ghiurau from the Human-Centric Lab at Volvo Cars for the support of the experiments. Many thanks to the participants, my friends and family for all the invaluable feedback and patience.

REFERENCES

[1] Andersson, R., Larsson, L., Holmqvist, K., Stridh, M., & Nyström, M. (2016). One algorithm to rule them all? An evaluation and discussion of ten eye movement event-detection algorithms. Behavior Research Methods.

[2] Andrienko, G., Andrienko, N., Burch, M., & Weiskopf, D. (2012). Visual analytics methodology for eye movement studies. IEEE Transactions on Visualization and Computer Graphics, 18(12), 2889-2898.

[3] Ankerst, M., Breunig, M. M., Kriegel, H. P., & Sander, J. (1999). OPTICS: ordering points to identify the clustering structure. ACM Sigmod record, 28(2), 49-60.

[4] Birant, D., & Kut, A. (2007). ST-DBSCAN: An algorithm for clustering spatial-temporal data. Data & knowledge engineering, 60(1), 208-221.

[5] Blascheck, T., Kurzhals, K., Raschke, M., Burch, M., Weiskopf, D., & Ertl, T. (2017). Visualization of eye tracking data: A taxonomy and survey. In Computer Graphics Forum 36(8), 260-284.

[6] Blignaut, P. (2009). Fixation identification: The optimum threshold for a dispersion algorithm. Attention, Perception, & Psychophysics, 71(4), 881-895.

[7] Duchowski, A. T. (2007). Eye tracking methodology. Theory and practice, 328(614), 2-3.

[8] Goldstein, E. B., & Brockmole, J. (2016). Sensation and perception. Cengage Learning.

[9] Hessels, R. S., Niehorster, D. C., Kemner, C., & Hooge, I. T. (2017). Noise-robust fixation detection in eye movement data: Identification by two-means clustering (I2MC). Behavior research methods, 49(5), 1802-1823.

[10] Larsson, G. (2010). Evaluation Methodology of Eye Movement Classification Algorithms.

[11] Lawson, G., Salanitri, D., & Waterfield, B. (2016). Future directions for the development of virtual reality

within an automotive manufacturer. Applied ergonomics, 53, 323-330.

[12] Li, B., Wang, Q., Barney, E., Hart, L., Wall, C., Chawarska, K., ... & Shic, F. (2016). Modified DBSCAN algorithm on oculomotor fixation identification. In Proceedings of the Ninth Biennial ACM Symposium on Eye Tracking Research & Applications, 337-338.

[13] Li, S. W., Xu, Y., Sun, W. C., Yang, Z. F., Wang, L. H., Chai, M., & Wei, X. X. (2015). Driver fixation region division–oriented clustering method based on the density-based spatial clustering of applications with noise and the mathematical morphology clustering. Advances in Mechanical Engineering, 7(10), 1687814015612426.

[14] Olsen, A. (2012). The Tobii I-VT fixation filter. Tobii Technology, 1-21.

[15] Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., ... & Vanderplas, J. (2011). Scikit-learn: Machine learning in Python. the Journal of machine Learning research, 12, 2825-2830.

[16] Pfeiffer, T., & Memili, C. (2016). Model-based real-time visualization of realistic three-dimensional heat maps for mobile eye tracking and eye tracking in virtual reality. In Proceedings of the Ninth Biennial ACM Symposium on Eye Tracking Research & Applications, 95-102.

[17] Salvucci, D. D., & Goldberg, J. H. (2000). Identifying fixations and saccades in eye-tracking protocols. In Proceedings of the 2000 symposium on eye tracking research & applications, 71-78.

[18] Schubert, E., Sander, J., Ester, M., Kriegel, H. P., & Xu, X. (2017). DBSCAN revisited, revisited: why and how you should (still) use DBSCAN. ACM Transactions on Database Systems (TODS), 42(3), 1-21.

[19] Smith, M. (2018). Unity 2018 cookbook: over 160 recipes to take your 2D and 3D game development to the next level. Packt Publishing Ltd.

[20] Stylidis, K., Wickman, C., & Söderberg, R. (2015). Defining perceived quality in the automotive industry: an engineering approach. Procedia CIRP, 36, 165-170.

[21] Takahashi, R., Suzuki, H., Chew, J. Y., Ohtake, Y., Nagai, Y., & Ohtomi, K. (2018). A system for three-dimensional gaze fixation analysis using eye tracking glasses. Journal of Computational Design and Engineering, 5(4), 449-457.

[22] Tim H. (2019). Expert eye tracking tips. https://www.tobiipro.com/blog/expert-eye-tracking-tips/

[23] Zeithaml, V. A. (1988). Consumer perceptions of price, quality, and value: a means-end model and synthesis of evidence. Journal of marketing, 52(3), 2-22.

APPENDIX 1 - EXPERIMENTAL SETUP

A1. Participant Recruitment

1. Six employees of Volvo Cars, including two AR/VR developers from the Human-Centric Lab, four designers/engineers from the Perceived Quality team, participated in the eye-tracking experiments.
2. All the participants were consent to the intention, process, and data usage of the experiments. All the data collected were processed confidentially within the organization.
3. All the participants had no visual acuity, three of them were wearing glasses, no one was wearing contact lenses. The design of experiment has not enough taken **inclusivity and accessibility** into consideration, which is regarded as a delimitation of the study.

A2. Viewing Tasks and Other Observations

1. Each experiment session lasted for six minutes. For the first 1.5 minutes, participants were asked to look at three components in the car interior (specified differently before each session), in the remaining 4.5 minutes participants explored the VR scene freely. The viewing tasks were used to evaluate the accuracy of the fixation identification algorithms and therefore produce tuning suggestions for them.
2. Context of the virtual car inspection is a digital car showroom scenario where customers (buyers) and car designers inspect the car, not in driving, or other traffic scenarios.
3. The VR hardware would hijack the reviewer's screen so that the visualization tool was not interactable when an eye-tracking experiment was running. Visualizations were reviewed on the computer's monitor (flat screen) in most of the time. However, it is possible to explore the scene with visualizations after they are rendered.
4. The ideal sampling rate of the VARJO 20/20 Eye Tracker is 100Hz in the "OneGazePerFrame" logging mode, but it dropped to 8~30Hz with the workload on running. Around 30,000 gaze points were recorded in total.