Spatio-temporal integration properties of the human visual system

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DOI:
10.33612/diss.136424282

Appendices

Thesis Summary

Visual perception has a fundamental role in supporting our interactions with the environment, yet not all visual information is needed for this purpose. In order to be able to efficiently process the tremendous amount of continuously incoming information, our visual system needs to compress this stream both spatially and temporally. It has to do this in a way that is somewhat analogous to how computers compress videos in MPEG format: the relevant information is retained, but it now requires a fraction of the memory to be stored. In the visual brain, this process is called spatio-temporal integration of visual information, and it is implemented through distributed neural networks that involve both cortical and subcortical structures. Therefore, the quantification of these integration processes may provide useful insights into the structural and functional integrity of the central nervous system.

However, quantitative models of spatio-temporal integration are relatively rare, and existing ones are mostly confined to understanding the process in theoretical and/or experimental contexts. With the work presented in this thesis, I have taken two steps towards overcoming these limitations. First, I have deepened our theoretical and quantitative understanding of spatio-temporal integration. To do so, I combined psychophysics, and computational modeling to build and test a model of how attention affects the integration of visual information as occurs in peripheral visual crowding.

Second, I have bridged the gap between our scientific understanding of integration and using this knowledge in clinical practice. For this, I combined eye-tracking with signal processing and artificial intelligence to extract clinically-relevant information

from eye movements recorded while participants performed a task requiring spatio-temporal integration of visual information (i.e. continuous tracking). The main results of my research are:

- A neurobiologically plausible computational model that explains how attention modulates the visual-spatial information integration underlying crowding: spatial attention modulation resulted in a spatially-selective reduction in integration strength, while feature-based attention modulation induced a more modest global reduction. The outcomes of this model matched those of a psychophysical experiment that showed that spatial and feature-based attention had different effects on crowding strength.
- A mathematical framework based on continuous psychophysics to extract the spatio-temporal properties of eye movements.
- A fast, multi-purpose eye movement-based test incorporating this framework that we called SONDA (Standardized Oculomotor and Neuro-ophthalmic Disorder Assessment). This test allows us to perform a thorough neuro-ophthalmic screening as well as to perform a high-resolution measuring of visual field sensitivity in a user-friendly way.

My findings show how spatio-temporal integration is a flexible process in the visual system, of which the properties change depending on different contexts in which it has to operate. Furthermore, I showed how these properties can be leveraged to create a very effective and efficient set of neuro-ophthalmic tools.

Nederlandse Samenvatting

Visuele perceptie speelt een fundamentele rol bij het ondersteunen van onze interacties met de omgeving, maar hiervoor is niet alle aanwezige visuele informatie nodig. Om de enorme hoeveelheid continu binnenkomende informatie efficiënt te kunnen verwerken, moet ons visuele systeem deze informatiestroom zowel in plaats als in tijd beperken, op een manier die analoog is aan hoe computers video in MPEG formaat comprimeren: de relevante informatie is er nog steeds, maar de benodigde ruimte voor opslag is vele malen kleiner. In de visuele hersenen wordt dit proces spatio-temporele integratie van visuele informatie genoemd en ontvouwt het zich over complexe neurale netwerken die zowel corticale als subcorticale structuren omvatten. Daarom kan de kwantificering ervan nuttige inzichten verschaffen in de structurele en functionele integriteit van het centrale zenuwstelsel.

Kwantitatieve modellen van spatio-temporele integratie zijn echter relatief schaars en de meeste zijn beperkt tot een theoretische of experimentele context. Met het werk dat in dit proefschrift wordt gepresenteerd, wil ik twee stappen voorwaarts zetten om de kloof tussen het laboratorium en de klinische praktijk te overbruggen.

De eerste stap betreft het begrijpen hoe spatio-temporele integratie kwantitatief kan worden gemodelleerd in twee verschillende visusgerelateerde contexten: oogbewegingen en perifere visuele crowding. De tweede stap betreft het gebruiken van deze nieuwe inzichten over spatio-temporele integratie voor het ontwikkelen van instrumenten die kunnen helpen om klinische problemen op te lossen. Voor dit doel heb ik het registreren van oogbewegingen, signaalverwerking en kunstmatige intelligentie gecombineerd om klinisch relevante informatie uit oogbewegingen te halen. Bovendien combineerde ik psychofysica en rekenkundig modelleren om te onderzoeken hoe aandacht de integratie van visuele informatie zoals die optreedt bij visuele crowding beïnvloedt.

De belangrijkste resultaten van mijn onderzoek zijn:

- Een wiskundig raamwerk om de spatio-temporele eigenschappen van oogbewegingen te extraheren uit continue registraties van oogbeweginen.
- Een snelle, multifunctionele, op oogbewegingen gebaseerde test waarin dit raamwerk is opgenomen en dat we SONDA (Standardized Oculomotor and Neuro-ophthalmic Disorders Assessment) hebben genoemd. Deze test stelt ons in staat om een grondige neuro-ophthalmologische screening uit te voeren (bijvoorbeeld gericht op MS of de ziekte van Parkinson) en op een gebruiksvriendelijke manier een gezichtsveldtest uit te voeren.

- Een neurobiologisch plausibel rekenkundig model dat uitlegt hoe aandacht de visueel-ruimtelijke informatie-integratie die ten grondslag ligt aan crowding moduleert: ruimtelijke aandachtsmodulatie resulteerde in een plaats-specifieke, en in mindere mate ook globale, vermindering van de integratiekracht. De uitkomsten van dit model kwamen overeen met die van een psychofysisch experiment dat aantoonde dat ruimtelijke en kenmerkgebaseerde aandacht verschillende effecten had op druksterkte.

Deze bevindingen laten zien hoe integratie van visuele informatie in ruimte en tijd een flexibel proces is in het visuele systeem, waarvan de eigenschappen veranderen afhankelijk van verschillende contexten. Ik heb deze eigenschappen gebruikt om een zeer effectief klinisch hulpmiddel te creëren.

Publications List

Articles

1. **Grillini, A.**, Ombelet, D., Soans, R. S. and Cornelissen, F. W. (2018). Towards Using the Spatio-temporal Properties of Eye Movements to Classify Visual Field Defects. *In ETRA '18: 2018 Symposium on Eye Tracking Research and Applications, June 14–17, 2018, Warsaw, Poland. ACM, New York, NY, USA, Article 4, 5 pages.* doi:/10.1145/3204493.3204590

2. **Grillini, A.**, Renken, R. J., and Cornelissen, F. W. (2019). Attentional Modulation of Visual Spatial Integration: Psychophysical Evidence Supported by Population Coding Modeling. *Journal of Cognitive Neuroscience. 31:9, 1329-1342* doi:/10.1162/jocn_a_01412

3. **Grillini, A.**, Renken, R. J, Vrijling, A. C. L., Heutink, J., Cornelissen, F. W. (2020) Eye movement evaluation in Multiple Sclerosis and Parkinson's Disease using a Standardized Oculomotor and Neuro-ophthalmic Disorder Assessment (SONDA). *Frontiers in Neurology*. doi: 10.3389/fneur.2020.00971

4. Hernández-García, A., Gameiro, R. R., **Grillini, A.**, König, P. (2020) Global visual salience of competing stimuli. *Journal of Vision. 20(7):27* doi:https://doi.org/10.1167/jov.20.7.27.

5. Gestefeld, B., **Grillini, A.**, Marsman, J. B., Cornelissen, F. W. (2020) Using natural viewing behavior to screen for and reconstruct visual field defects. *Journal of Vision* (in press)

6. Gnolo, C., Senden, M., **Grillini, A.**, Cornelissen, F.W., Goebel, R. (2018) Configural properties underlie the perceived faceness of a stimulus. *bioRxiv 509026*; doi: https://doi.org/10.1101/509026

7. **Grillini, A.**, Hernández-García, A., Renken, R. J., Demaria, G., Cornelissen, F. W. (2020) Computational methods for continuous eye-tracking perimetry based on spatio-temporal integration and a deep recurrent neural network. (under review)

8. **Grillini, A.**, Kromm, M., Renken, R. J., Cornelissen, F. W. (2020) Motion sensitivity assessment based on an analysis of the spatio-temporal features of eye movements. (under review)

9. **Grillini, A.**, Koens, L. H., Lange, F., Rutkauskaite, G., Cornelissen, F. W., Tijssen, M.A.J. (2020) A comparison between quantitative assessments of saccades in adult patients with Niemann-Pick type C. (under review)
10. Soans, R. S., **Grillini, A**., Saxena, R., Renken, R. J., Gandhi, T. K., Cornelissen, F. W. (2020) Eye-movement-based assessment of the perceptual consequences of glaucomatous and neuro-ophthalmological visual field defects. (under review)

Patent

Grillini, A., Hernández-García, A., Renken, R. J. (2019). Method, system and computer program product for mapping a visual field. *European patent application EP19209204.7.*

Acknowledgments

First, I would like to express my gratitude to my academic supervisors: Frans Cornelissen, Nomdo Jansonius and Remco Renken.

Dear Frans, your open-mindedness, inquisitive spirit and poised demeanor played a crucial role in my research work as much as your scientific advice. To me, you have been way more than just a supervisor: a reassuring figure always present but never invasive. I probably have not been the easiest PhD student to manage but, for having always trusted me (and my wacky ideas), I sincerely thank you.

Dear Nomdo, your wisdom and unrivalled knowledge in Vision have been and will always be a great source of inspiration to me. Every single minute spent discussing ideas with you have proved to be of incredible value for my scientific work.

Dear Remco, whenever all hopes seemed lost you always taught me to stay positive while joyously embracing the inherent chaos that the scientific curiosity brings. To put it in other words (of a much smarter man than myself): *"all that is gold does not glitter, not all those who wander are lost"*.

Then, in no particular order, I would like to thank:
prof. Marina de Koning-Tijssen, prof. Peter König and prof. Raymond van Ee, who formed the reading committee of my thesis. Many thanks for your time and your valuable feedback.

My colleagues at the LEO, who made the daily-life at the office always pleasant and enjoyable: Joana, Hinke, Nico, Barbara, Funda, Sandra, Shereif, Marouska, Elouise, Azzurra, Birte, Rijul, Ronald, Bart, Giorgia, Lorenzo, Konstantinos, Allison, Anna, Catarina, Tuomas, Valeria, Asterios, Sina and all the "EGRETters". I wish you all the best in your respective careers. Many thanks to the "big boss" of the NIC, Hedwig, who every day put up with my stumbling dutch, and has always been incredibly helpful. One day you will get the tiramisù I promised!

The whole NextGenVis gang, the craziest, most beautiful group of neuroscientists I have ever had the pleasure to work with: Hinke & Jo (you both deserve double thanks!), Alex, Carmine, Marc, Jan, Stas, Freja, Robert, Babs, Jelle, Akhil, Akshatha, Khazar, Peter (and Koulla as honorary member). All the trips across Europe and the Jägerbombs-filled nights will stay forever in my heart. Still from NextGenVis, a special thanks goes to Nadine Schmieder-Galfe for her business advice always delivered with a smile and for her help in dealing with intellectual property.

The friends from all over the world that I made along the way: Malte, Diego, Ronja, Henri, Berit, Kaweh, Baba, Michael; and the friends from Italy who have been with

me since forever: Cioni, Bocca, Mello, Sicci, Ginko, Gonne, Andre, Giangi, Simo & Ste. Not a single day has passed without at least a couple of you cheering me up with some random stupid stuff. Love you all.

My Dutch teacher and *wandeling* partnern Jacques. Hartelijke dankjewel voor al onze gesprekken en jouw hulp bij de nederlandse samenvatting van dit proefschrift.

The VentureLab family, the business coaches and the "highlanders" of Group 8: prof. Aard Groen, Aniek, Olga, David, Jürgen, Chris, Rachel, Erik, Anne, Hoang, Ronald, René, Stéfanie and Raymond. May your future endeavors be as bright as your personalities.

My whole family in Italy (and I mean *everyone*), which always showed me an unconditioned and tremendous level of support: poche parole in italiano non basteranno mai a ringraziarvi per tutto quello che avete fatto per me e tutto l'affetto che mi avete dimostrato, ma tant'è...grazie di cuore a tutti voi.

My girlfriend Maria. In these years you have been my compass, my best friend, my sanity keeper, my adventure partner, my co-author and so much more. Спасибо за всё, Маша. я тебя люблю.

Last, but surely not least, a thought for my grandfather, who would have been the proudest of them all: Nonno, ce l'abbiamo fatta. Ovunque tu sia, sempre con me.

Alessandro Grillini
August 2020
Groningen, The Netherlands