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Final Report. How catchy are own eye-gaze replays? A qualitative study exploring the use of students' eye-gaze stimulated retrospectives in organic chemistry – i-GAZE

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Final Report

How catchy are own eye-gaze replays?

A Qualitative Study Exploring the Use of Students' Eye-Gaze Stimulated Retrospectives in
Organic Chemistry – i-GAZE



1. General information

DFG reference number: GR 4003/7-1
Project number: 453926661
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Reporting period: 10/2021 - 09/2024, extended until 10/2025 cost-neutrally due to the Corona pandemic.

2 Summary

The i-GAZE project investigated how recordings of students' own eye movements can be used both as a window into their problem-solving with organic representations and as a starting point for supporting student reflection. The project implemented an eye-gaze-augmented retrospective in which students solved typical organic chemistry tasks, watched replays of their eye movements, and reflected on their approaches in structured phases.

The qualitative study on reflection processes shows that such a retrospective can provoke a wide range of reflection patterns and that a large proportion of these patterns reach a high structural complexity when students are confronted with the task solution and targeted prompts, especially when they have previously solved a problem inaccurately. In these cases, students describe their experience in detail, identify difficulties, evaluate their approaches and derive consequences for future tasks. The retrospective thus offers a promising way to turn struggles into productive learning opportunities and to make individual visual and conceptual difficulties explicit.

At the same time, the project has contributed important methodological developments. With Δ Gaze, an integrated measure was introduced that summarises the change in eye movements across multiple metrics and allows the extent of visual change between tasks to be characterised in a compact form. Applied in two studies, one without and one with instruction, Δ Gaze revealed differentiated patterns that link instructional interventions, such as eye-gaze-augmented retrospectives, to changes in visual behaviour and performance. With the Limited-

Radius-Voronoi Tessellation method, a systematic approach was additionally developed for defining Areas of Interest (AOI) in complex organic representations, thereby increasing the transparency and comparability of AOI-based analyses.

Overall, the project demonstrates that eye-tracking, when combined with carefully designed retrospectives and methodological tools, can offer both rich insights into students' interaction with representations and concrete levers for instructional design. The results underline that the processing of representations and problem-solving is highly individual and that one-size-fits-all interventions may not always address the full range of students' needs. Instead, the findings point towards more adaptive and differentiated forms of support, in which eye-gaze information and reflection prompts are used to foster each student's development of representational competence in a targeted manner.

3 Progress Report

Background and objectives of the project

The i-GAZE project builds on a long line of research that has shown that students in organic chemistry often interpret structural representations in a strongly surface-oriented manner and have difficulties linking explicit visual features to implicit properties and concepts (e.g., Graulich, 2015; Graulich *et al.*, 2019; Dood & Watts, 2023; Graulich, 2025). As a result, their problem-solving is frequently guided by salient but not necessarily relevant cues, and they tend to rely on rules of thumb instead of integrating conceptual information into their reasoning.

In the project, this learning difficulty was conceptualized as an ongoing interplay of visual and conceptual processing (Bowen & Roth, 2002; Schnotz & Bannert, 2003). Supporting this integration of visual and conceptual elements requires not only instructional designs that guide attention (e.g., Wermeskerken *et al.*, 2018; Roach *et al.*, 2019; Rodemer *et al.*, 2022) but also opportunities for students to become aware of, and to reflect on, their own approaches while decoding chemical representations (Hansen *et al.*, 2019).

In line with this goal, researchers have used recorded eye movements of experienced problem solvers as cues to align students' attention with that of the model (van Gog *et al.*, 2009; Litchfield *et al.*, 2010; Jarodzka *et al.*, 2013). Replays of others' eye-gaze patterns externalize the expert's perceptual decoding process for the observer, who can adopt the expert's perspective and better understand the expert's task solutions and fixation preferences (Zelinsky *et al.*, 2013; Foulsham and Lock, 2015). Although studies using eye-movement modeling examples have demonstrated that learners' visual behavior adapts to the model's eye-gaze behavior (Jarodzka *et al.*, 2012), it remained unclear what learners would have been able to do without such support and whether they are aware of changes in their own eye-gaze behavior. Additionally, an exploratory study to determine 'ideal' model-observer matches for eye-movement modelling examples in chemistry has not been possible (Graulich *et al.*, 2022).

Building on prior work, the project pursued the central idea of using students' own eye movements as a resource for learning. Eye-gaze replays promise to make normally inaccessible aspects of problem-solving visible and to offer a basis for systematic reflection on one's own decoding processes (Hyrskykari *et al.*, 2008). The original objectives of the project can be summarised in three guiding questions:

- 1 | How can students' visual and conceptual processing be characterised when their reflection is stimulated by their own eye-gaze replays?
- 2 | To what extent do different reflection phases foster reflection processes?
- 3 | How are eye-gaze-based retrospectives related to changes in students' eye movements over time, and how can these changes be captured methodologically?

Progression of the project

The work plan envisaged the development of complex yet prototypical tasks from organic chemistry, the implementation of an eye-gaze-augmented retrospective aligned with established models of reflection, and the qualitative analysis of students' reflection processes based on verbal and eye-tracking data. Data collection was planned in the context of an Organic Chemistry 1 course at a German university, with a special focus on structural sites of organic molecules that are known to be challenging for students, such as asymmetric carbon atoms or typical electrophilic and nucleophilic centres (see Figure 1).

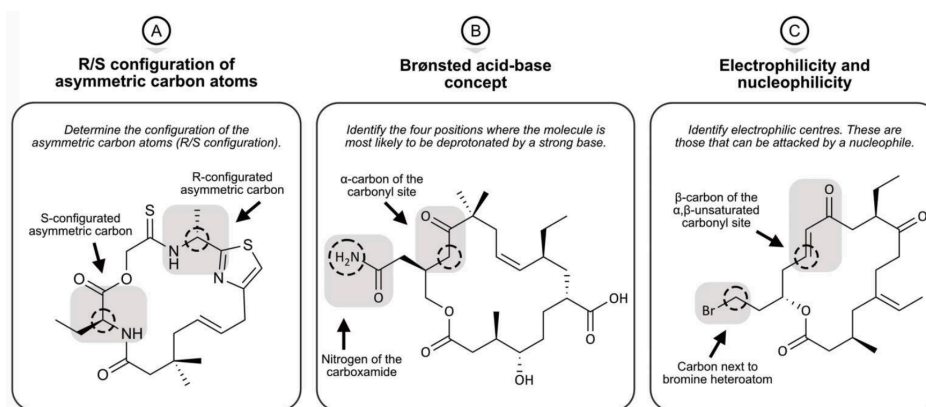


Fig. 1: Three task sets used. A: Stereochemistry context, B: Acid-base context, C: Electrophilicity. Highlighted in grey are the structural areas and the circles indicate the solution students should select (not visible)

The core design of the project proposal was realised as planned. In comparison to the original project proposal, we used the ALACT model of reflection by Korthagen (1985) to structure the three phases of the retrospective with carefully designed prompts. By focusing on *Action*, *Looking back*, *Awareness*, *Create*, *Trial*, we were able to explore the participants' experiences in a stepwise manner. In the context of our study, two purposefully designed and comparable molecular structures were used in the *Action* and *Trial* phase, and students were prompted to solve them silently. Students' eye movements were recorded with a Tobii screen-based eye tracker while they solved each task mentally and then wrote down their answer. After the first *Action* phase, students went through a three-phase retrospective (1. *Looking back*, 2.

Awareness, 3. *Creating alternatives*) that maps onto the post-action phases in the overall ALACT model, before completing the *Trial* phase (see Figure 2).

In the *Looking back* phase, students watched a video replay of their own eye gaze on the respective molecular representations. The replay ran at half speed; students could pause, jump back/forward, and re-watch. They were asked to think aloud retrospectively, reconstructing what they had looked at and thought while solving the task. So, this phase operationalized *Looking back* with the help of an eye-gaze replay. In the next phase *Awareness of essential aspects*, students watched the eye-gaze replay again and were now asked with targeted reflection prompts to help them identify issues, evaluate their approach and begin to articulate consequences. This phase is where students are nudged toward recognising what in their viewing and reasoning was crucial, problematic, or helpful.

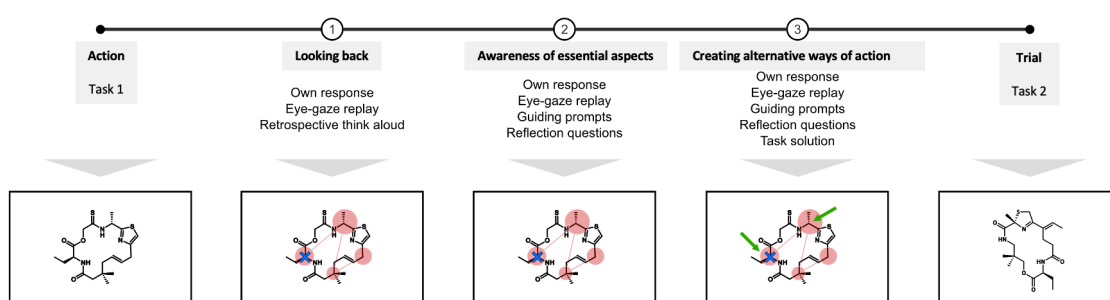


Fig. 2: Outline of the interview design along the adapted phases of the model of reflection (Korthagen, 1985)

In *Creating alternative ways of action*, the correct task solution was added as an overlay to the eye-gaze replay and the student's answer. With similar prompts, students compared their own viewing/solution with the model solution and were explicitly encouraged to formulate alternative strategies for future problems (visually and conceptually).

The data analysis process, in the first part of the project, focused on the reflection process during the retrospective, delineating the contributions of the three reflection phases (1. *Looking back*, 2. *Awareness*, 3. *Creating alternatives*). It became clear that students' complexity of reflection could not validly be determined by looking at the overall process, as students varied largely depending on the structural site they were looking at. In order to facilitate and structure the analysis, we decided to focus on areas of interest in the molecule that were structurally identical in the pre- and post-task to allow a correlation with students' overall success in these tasks. Thus, the analysis shifted from characterizing students' individual reflection processes to students' reflections on structural sites, resulting in 132 single reflection processes.

During data analysis, it also became evident that the original qualitative focus needed to be complemented by the development of more systematic methodological tools. On the one hand, the definition of Areas of Interest (AOIs) in dense organic structures proved to be critical for the interpretation of eye-tracking data, as minor changes in AOI boundaries could lead to different conclusions. On the other hand, existing approaches that describe eye movements by individual metrics, such as fixation duration or number of transitions, did not sufficiently

reflect the multifaceted changes in students' visual behaviour across tasks. For instance, the eye-tracking data did not reveal a specific viewing pattern in relation to students' performance, as one would at least expect for the stereochemistry task (see task A in Fig. 1). These insights led to two extensions of the project: 1. the development of a systematic method for defining AOIs using limited-radius Voronoi tessellation (Langner *et al.*, 2025a), and 2. the conception of an integrated change measure, Δ Gaze, which aggregates the change across multiple eye-tracking metrics (Langner *et al.*, 2025b).

Furthermore, during the analysis of the eye-tracking data, the question arises why a student's eye gaze actually changes and if this is due to slight variations in the stimuli (relevant areas were rotated) or by being prompted to change due to the retrospective. Thus, the methodological work was extended to a second institutional context. Due to a collaboration with an international institution (Prof. Maia Popova, University of Greensboro, NC), a second data set could be collected in a comparable Organic Chemistry course. In this data collection, students only solved task A in the *Action* and *Trial* phase, while their eye movements were recorded, but these participants did not undergo the three reflective phases. This extension allowed the new methodological approaches, such as determining Δ Gaze.

With regard to handling research data, all anonymised research data (transcripts and eye-tracking data) and accompanying documentation are archived on a secure, access-restricted external storage medium at the JLU after completion. Selected datasets that are suitable for secondary use are available for reuse upon request and, where applicable, under a data use agreement that reflects consent as well as legal and ethical requirements.

Overall, the progression of the work followed the original objectives but gradually shifted the emphasis from solely exploring eye-gaze-augmented retrospectives to developing methodological solutions for capturing changes in students' visual behaviour. This development is reflected in the three publications resulting from the project.

Presentation of the results

The results of the project can be grouped into three interrelated strands: the empirical characterisation of reflection processes in an eye-gaze-augmented retrospective (**part 1**), the introduction of a systematic approach to AOI definition for organic representations (**part 2**), and the development of an integrated measure for changes in eye movements (**part 3**).

Part 1: Students' reflection processes

The main part of the project focused largely on research questions 1 and 2. First, it aimed at characterizing the structural complexity of undergraduate organic chemistry students' reflection processes when an eye-gaze-augmented retrospective stimulates those processes (Langner & Graulich, 2024). Second, because the retrospective is deliberately aligned with the three ALACT phases (see Fig. 2), we also investigated how each phase

contributes to structurally complex reflection processes and how this development depends on whether students solved the problem accurately or not. For the analysis, we selected two “typical structural sites” per task – for example, the carbon adjacent to the halogen atom in the electrophilicity task (see C in Fig. 1, structural sites highlighted in grey) – so that the reflection data could be anchored in specific, conceptually relevant positions in the molecules, yielding a total of 132 single reflection processes. Each reflection process at a given site was coded dichotomously for the presence or absence of four reflection elements derived from the reflection literature (Nguyen *et al.*, 2014): describing the experience (E), identifying an issue (I), evaluating an approach (A), and drawing a consequence (C). Based on the co-occurrence of these elements across phases, five reflection patterns with increasing structural complexity were distinguished: descriptive reflection, non-elaborated reflection, approach-centred reflection, consequence-centred reflection, and elaborated reflection (see Fig. 3). Reflection processes with only E or E+I were classified as lower complexity; processes including evaluation and/or consequences were classified as higher complexity.

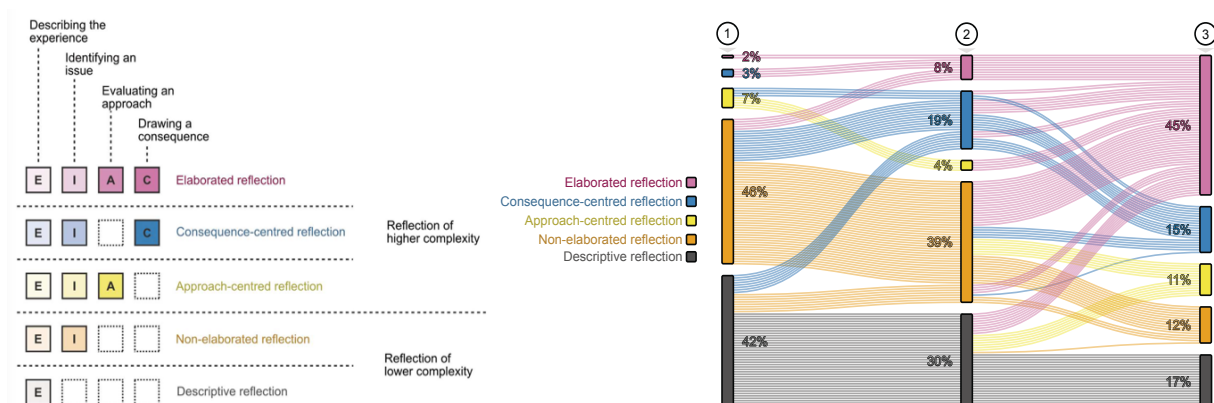


Fig. 3: Complexity levels from descriptive reflection to elaborated reflection (left); Changes in reflection complexity along the three reflection phases (right).

To capture the development of reflection over the three phases, codes were cumulated across phases so that elements introduced in later phases were added to those already present, and each reflection process was also classified according to whether the structural site had been determined accurately or inaccurately. The analysis thus showed that all students reached at least the *descriptive reflection* pattern because they were explicitly prompted to describe their problem-solving process. *Descriptive reflections* were limited to redescribing what they had done and thought. *Non-elaborated reflections* added explicit mention of difficulties, uncertainties, or challenges, but stopped short of evaluating approaches or formulating consequences. In contrast, the *approach-centred*, *consequence-centred*, and *elaborated reflections* involved evaluating one’s own or alternative approaches, drawing consequences for future problem-solving, or both, and were therefore taken as reflections of higher complexity. The element of “identifying an issue” appeared in all higher-complexity processes, indicating that awareness of a problem or difficulty often preceded more elaborated reflection.

The distribution and development of reflection patterns across the three phases revealed that the eye-gaze replay and prompts of the first two phases mainly helped students structure their descriptions and become aware of essential aspects but did not by themselves lead to strong shifts in reflection complexity. Major changes occurred in the third phase when the task solution was presented alongside reflection prompts, which may also not be surprising. The analysis further showed that the influence of the third phase depended on whether students had accurately solved the structural site. Confrontation with their own incorrect solution seemed to trigger discomfort, surprise, or confusion and thereby stimulated students to seek explanations, reconsider their approaches, and devise changes for the future. Overall, 71% of all analysed reflection processes across the study were structurally complex reflections, although a sizeable minority remained descriptive, especially on accurately solved sites.

We could, thus, document an indication that an eye-gaze-augmented retrospective can be used to stimulate reflection processes on problem-solving with representations, particularly for students who have not solved the problem accurately. At the same time, the current design does not fully exploit the potential of reflection for already successful students, nor does it systematically support conceptual sense-making beyond what students can bring from their prior knowledge. Future research should refine the design of such retrospectives and explore their integration into digital learning environments that can provide individualized support and adaptive prompts based on students' performance and data.

Part 2: Systematic approach to AOI definition in organic chemistry education

The second strand of results addresses the preparatory step of AOI definition, which is central for all AOI-based metrics used in the project. In the respective paper, the limited-radius Voronoi tessellation method (LRVT) is introduced for organic stimuli (Langner *et al.*, 2025a).

This addressed a central methodological challenge in eye-tracking research in organic chemistry: how to define areas of interest (AOIs) in complex structural representations in a way that is both chemically meaningful and systematically reproducible. Many current standard AOI approaches are not well suited to organic chemistry, where Lewis structures, cyclic systems, stereocenters and multistep mechanisms create dense, intricate visual fields. Up to now, most studies have relied on researcher-defined AOIs, which may introduce subjectivity and make it difficult to compare results across different structures and tasks. Existing AOI strategies, whether researcher-defined, stimulus-driven, algorithmically derived from gaze clusters, or grid-based, do not fully resolve the tension between the need for semantic precision and the need for reproducible procedures. We, thus, adopted the limited-radius Voronoi tessellation (LRVT) method and tailored it to organic chemistry stimuli.

Based on Voronoi's tessellation principle (Voronoi, 1909), the display is partitioned into cells such that each point belongs to the atom to which it is closest, within a predefined radius. Atom

coordinates are extracted directly from ChemDraw files and used to generate Voronoi cells, which are then intersected with a fixed radius to yield limited-radius AOIs around each atom. A key design decision was to define the LRV radius as the bond length of the depicted molecule. This choice ties the AOI size to a chemically meaningful and easily measurable parameter. It, thus, acknowledges characteristic features of organic stimuli and eye-tracking data: organic molecules often contain large areas of white space interspersed with dense local clusters, and salient structural features can attract attention at some distance from their geometric centers. The LRV AOIs tile the molecular region without gaps or overlaps, ensuring that every fixation within the molecule is assigned to exactly one AOI.

Interestingly, the LRV supports the analysis at different levels of granularity. Once atom-level (fine-grain) AOIs have been computed, they can be merged into larger, coarse-grain AOIs representing functional groups, ring systems, chains, or other structural units of interest, such as our structures used in the task sets. On a coarse-grain level, we defined AOIs that grouped broader regions, such as the ring framework or each stereocenter together with its substituents. On a fine-grain level, we retained individual AOIs for each atom around the stereocenters. This, for instance, allows us to analyze how fixations and transitions were distributed across specific substituents when students assigned R/S configurations.

This developed method can be extended to other representational forms central to organic chemistry. LRV does not eliminate the role of researcher judgment, but it provides a systematic baseline that can be refined when representation-specific issues arise. The development of this method facilitated the analysis of the eye-tracking data.

Part 3: Collaboration study with Prof. Maia Popova

The third strand of results concerns the question of how changes in students' eye movements can be described in an integrated way (Langner *et al.*, 2025b). In this work, two eye-tracking studies with stereochemistry tasks on the R/S configuration of chiral centres were conducted. In study I, students at a German university solved a pair of tasks, but between the tasks they participated in the eye-gaze-augmented retrospective, as described above. In study II, students at a US institution solved two analogous tasks in succession without instruction in between. This comparison became interesting as the original set-up did not allow conclusions about the extent to which a student's eye gaze actually changes. If this is based on slight variations in the stimuli or by being prompted to change due to the retrospective.

To describe students' changes in eye movements between the first and second tasks, we developed a new measure: Δ Gaze. This measure is defined as the average absolute, bounded, normalised change across several eye-tracking metrics which capture different aspects of information processing, such as fixation duration, fixation count, AOI hits, pattern frequencies, transitions and transition entropy. In this way, Δ Gaze reflects the overall magnitude of change in visual behaviour.

The application of Δ Gaze showed that even without explicit instruction in study II, students' eye movements can change considerably between comparable tasks. In the instruction condition, in study I, with the eye-gaze-augmented retrospective, patterns emerged that allowed us to link Δ Gaze more clearly to students' performance trajectories: students who maintained stable performance tended to show smaller values of Δ Gaze, whereas students whose performance improved or deteriorated showed larger changes in their eye movements. Case analyses show that similar values of Δ Gaze can be underpinned by different combinations of metric changes and must therefore always be interpreted in conjunction with detailed metric profiles and task contexts. Nonetheless, Δ Gaze provides a useful starting point for characterising the extent to which instruction influences students' visual behaviour. Taken together, these three strands of results from the overall project form a coherent whole. The eye-gaze-augmented retrospective study shows how students reflect on their own problem-solving when supported by eye-gaze replays. The Δ Gaze measure offers a way of following changes in their visual behaviour across tasks and interventions, and the LRV method provides a robust basis for defining AOIs in the first place. In combination, the project thus contributes both empirical insights into students' reflection processes and methodological tools that can be used in future eye-tracking-based instructional research.

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4 Published Project results:

4.1 Category A – Articles in peer-reviewed journals, contributions to peer-reviewed conferences or to anthology volumes, and book publications

1. Langner A. & Graulich N.* (2024), From sight to insight – reflection processes in an eye-gaze-augmented retrospective, *Int. J. Sci. Educ.*, 1–24. DOI: 10.1080/09500693.2024.2430804
2. Langner A., Hain L. S. & Graulich N.* (2025), Defining Areas of Interest in Organic Chemistry Education Eye-Tracking Research, *J. Chem. Educ.*, 102, 1285–1297. DOI: 10.1021/acs.jchemed.4c00830
3. Langner, A., Sahba, M., Popova, M., Graulich, N.* (2025) An Integrated Approach for Characterizing Changes in Organic Chemistry Students' Eye Movements, *J. Chem. Educ.*, accepted. <https://doi.org/10.1021/acs.jchemed.5c00849>

4.2 Category B – Any other form of published results

4. Langner, A. & Graulich, N. (2024) Mit Blick zurück einen Schritt vor: Eine blickbewegungs-gestützte Retrospektive, In: van Vorst, H. (Hrg.), Frühe naturwissenschaftliche Bildung, Gesellschaft für Didaktik der Chemie und Physik, Conference Hamburg 2023, p. 186-189.
5. Langner A. & Graulich N. (2024) Beim nächsten Mal - Halten sich Studierende an ihre eigenen Vorsätze bei zukünftiger Aufgabenbearbeitung?, POSTERPREIS der Fachgruppe Chemieunterricht, FGCU Tagung 2024.

4.3 Patents (applied for and granted) - Does not apply.