1 St Petersburg University

2 Perm Sate University

Towards Mitigating the Eye Gaze Tracking Uncertainty in Virtual Reality

This study is supported by the research grant No. ID75288744 from Saint Petersburg University, "Text processing in L1 and L2: Experimental study with eye-tracking, visual analytics and virtual reality technologies"

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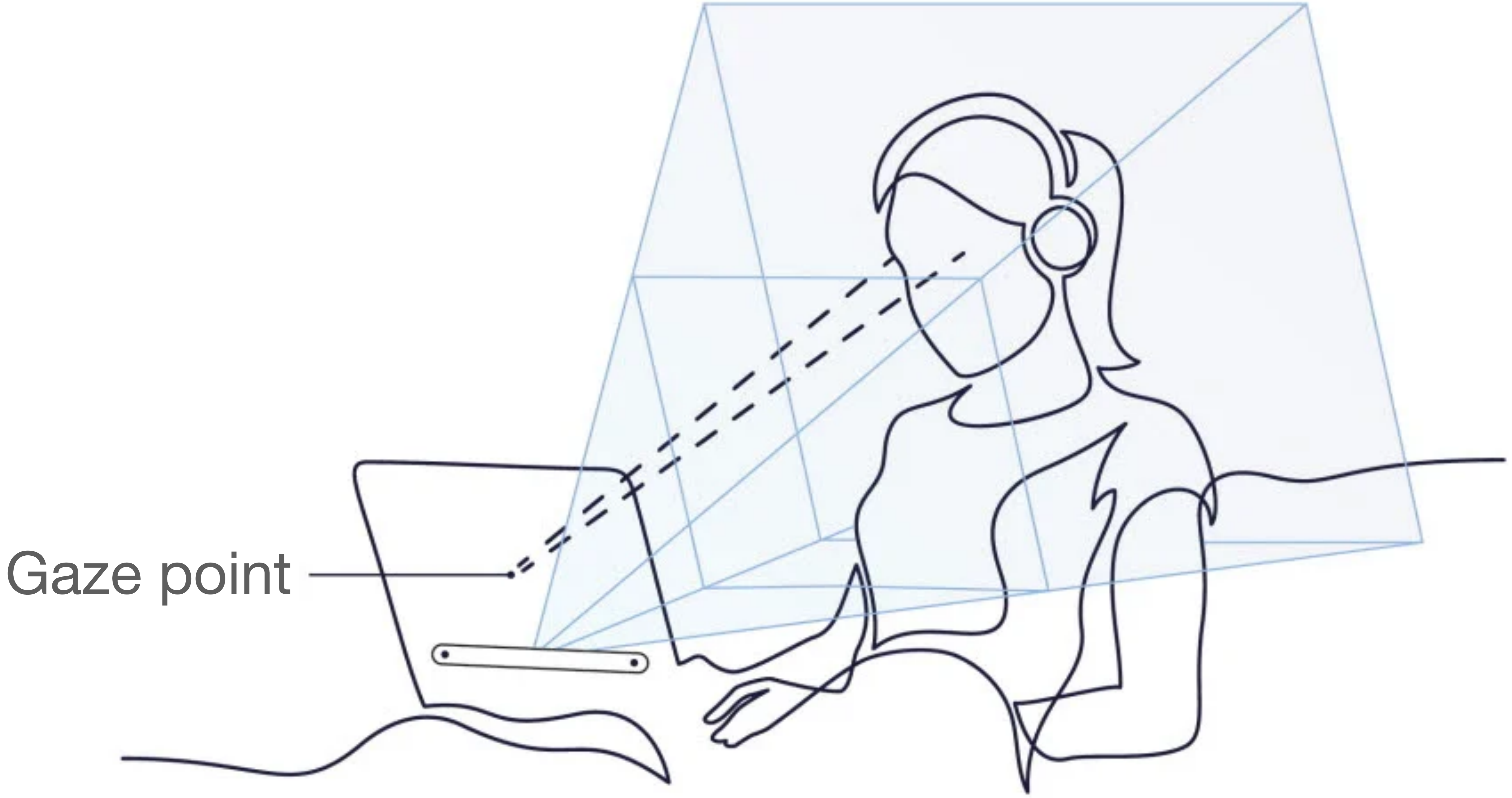
Perm-London – 2022

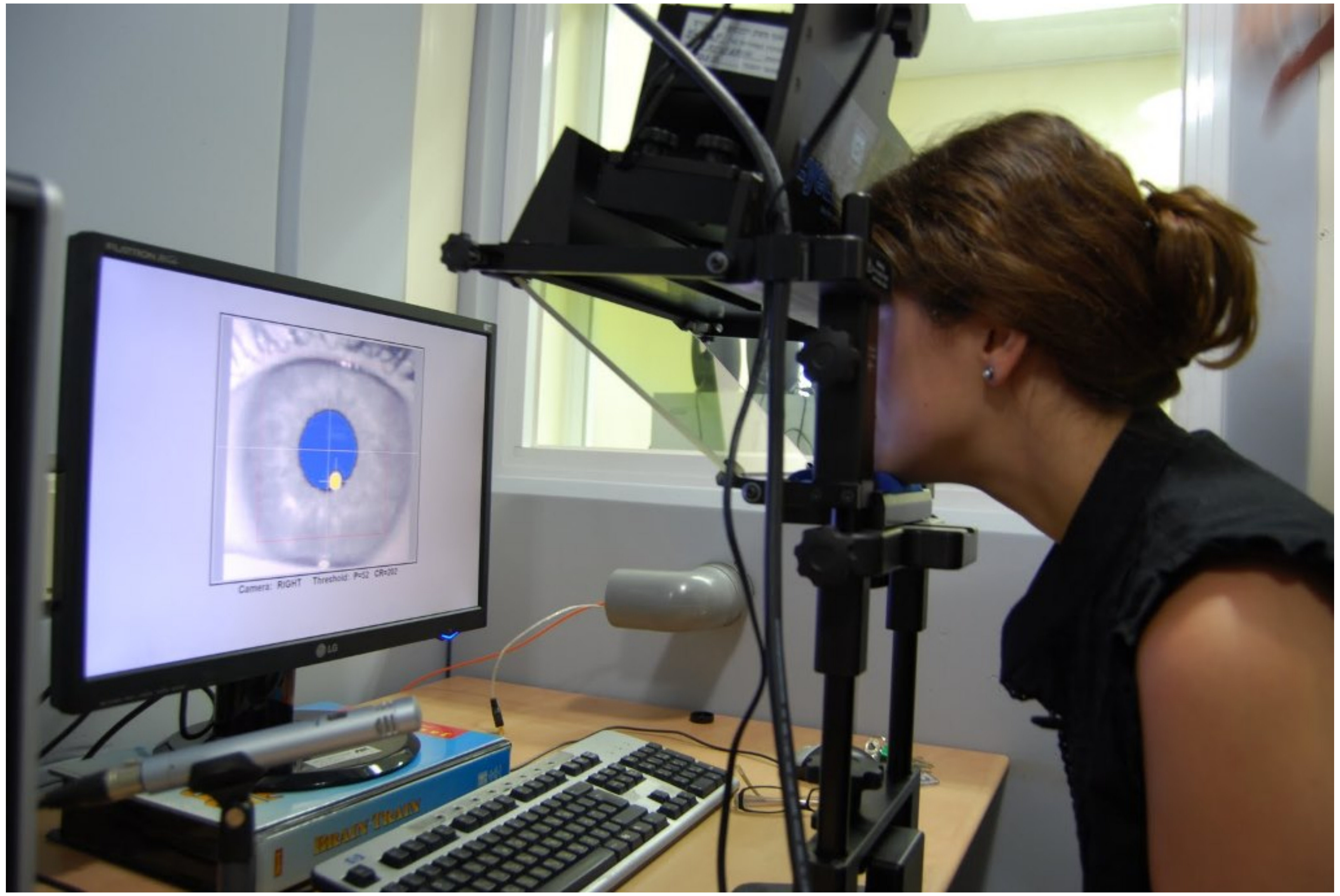
Methodology of studying the information perception based on tracking the eye gaze movements



(Holmqvist et al., 2017)

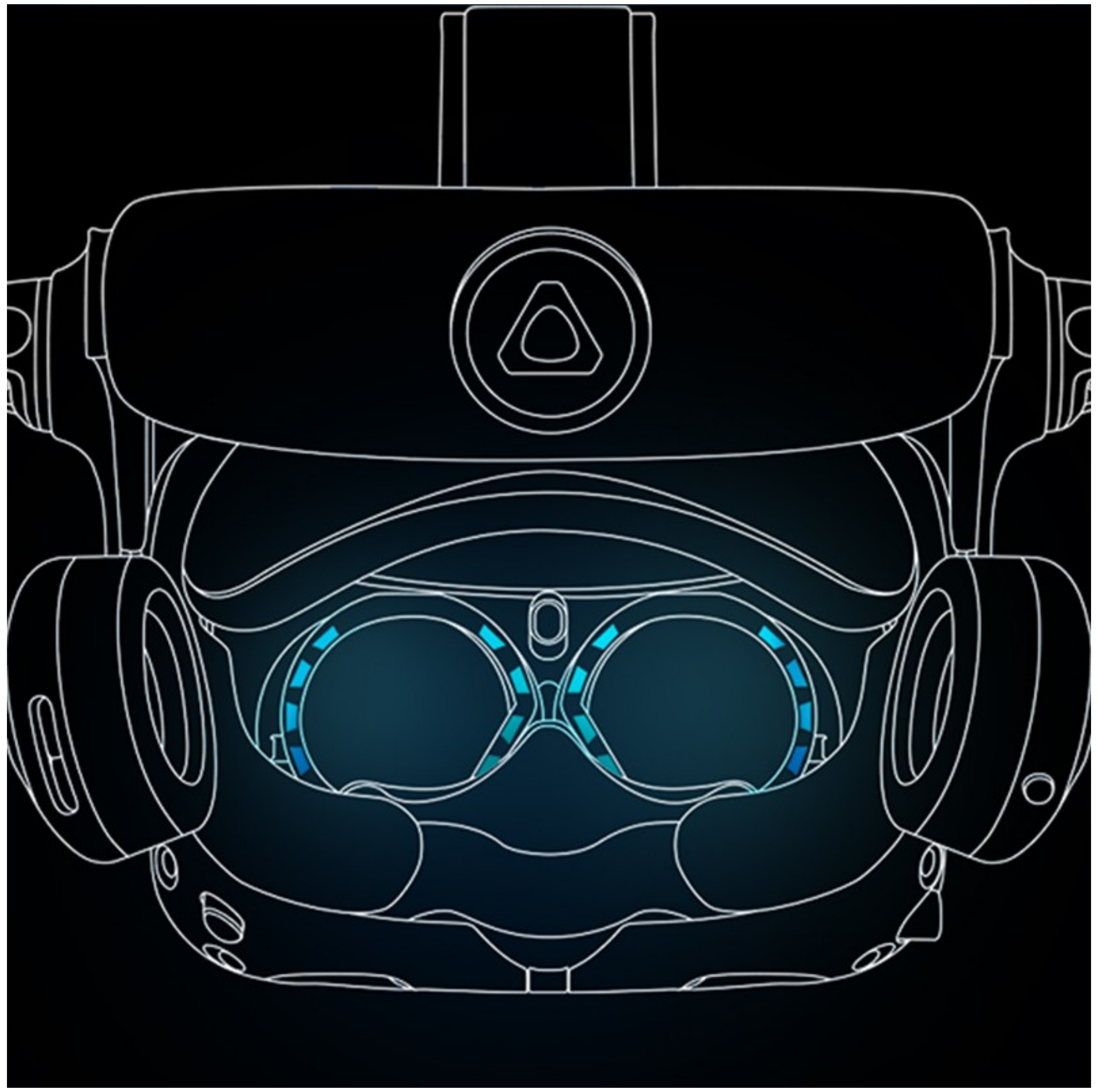
Eye Tracking: Traditional Approach

100+ years evolution of devices, algorithms and methods



(Shehu et al., 2021)

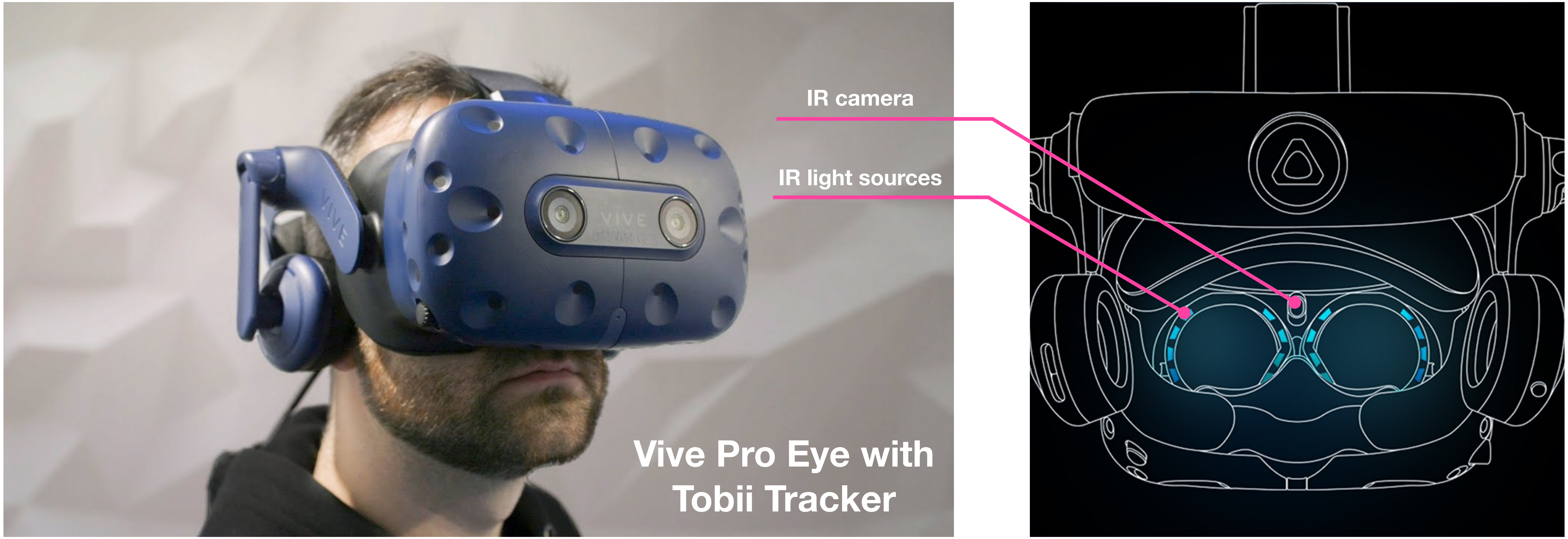
Recently, eye trackers are available in VR head-mounted displays



(Clay et al., 2019; Iacobi, 2018)

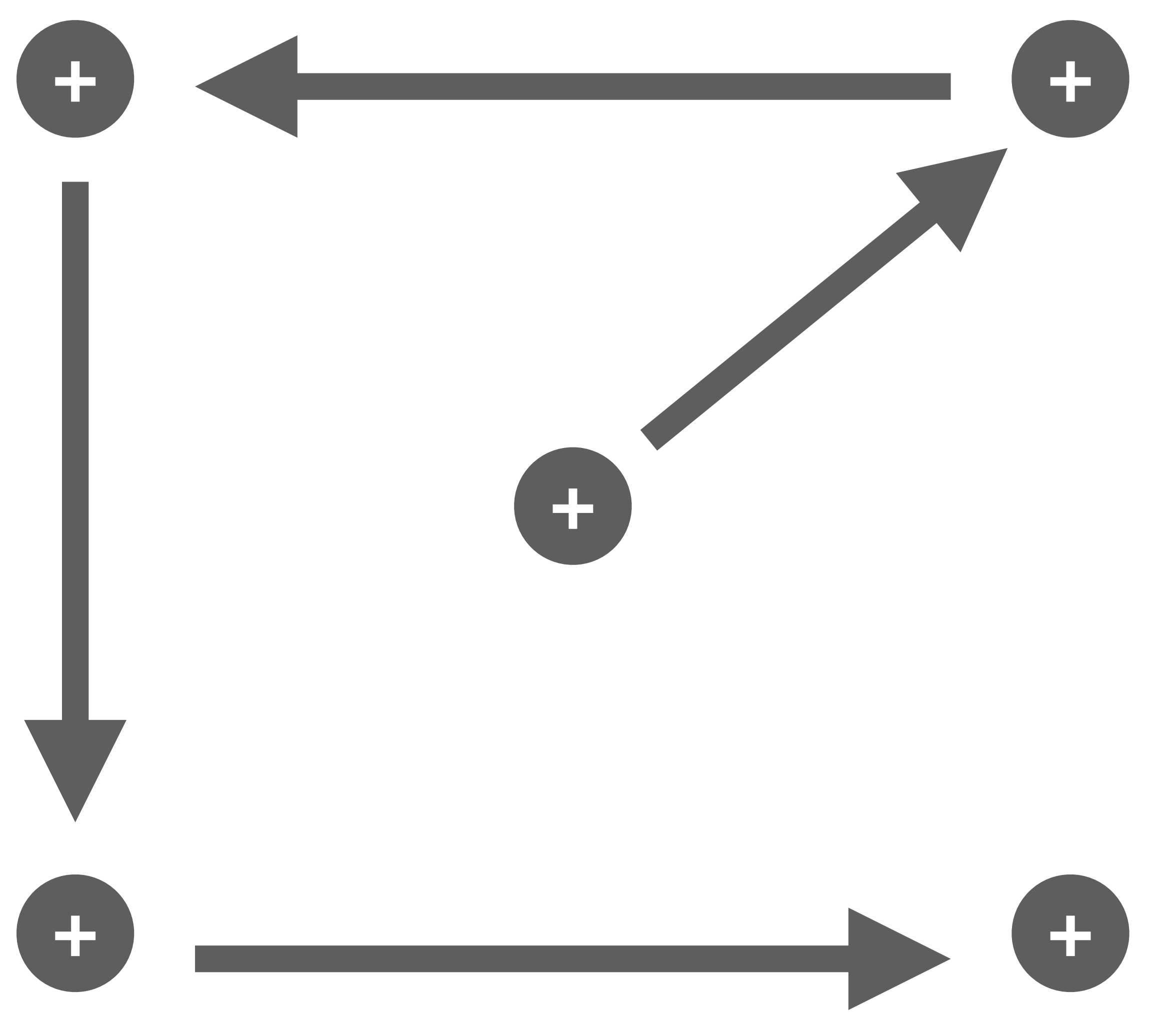
Eye Tracking: VR

Recently, eye trackers are available in VR head-mounted displays

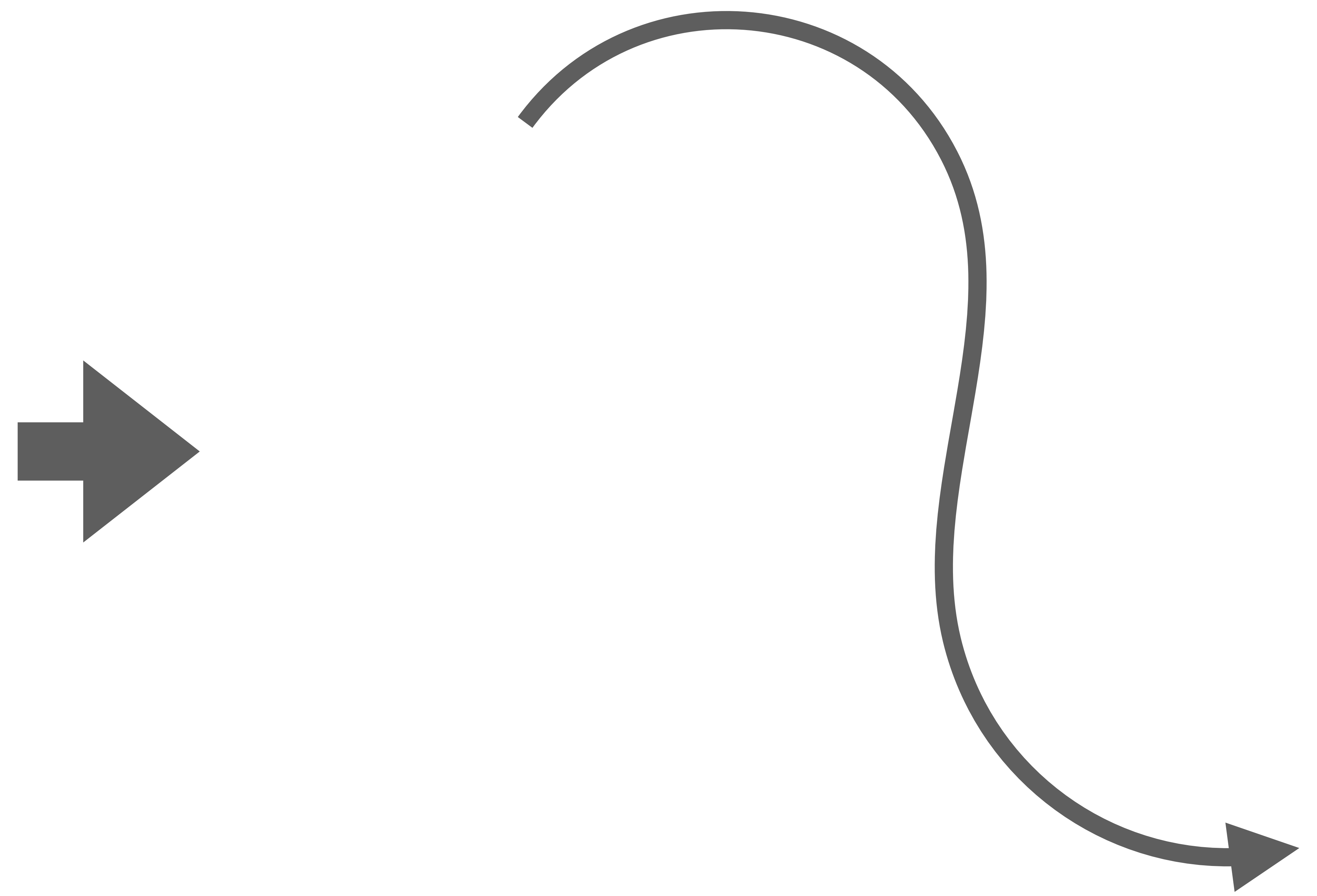


(Clay et al., 2019; Iacobi, 2018)

Eye Tracking: Operating Procedure



Calibration



Tracking

Who Needs Eye Tracking in VR?

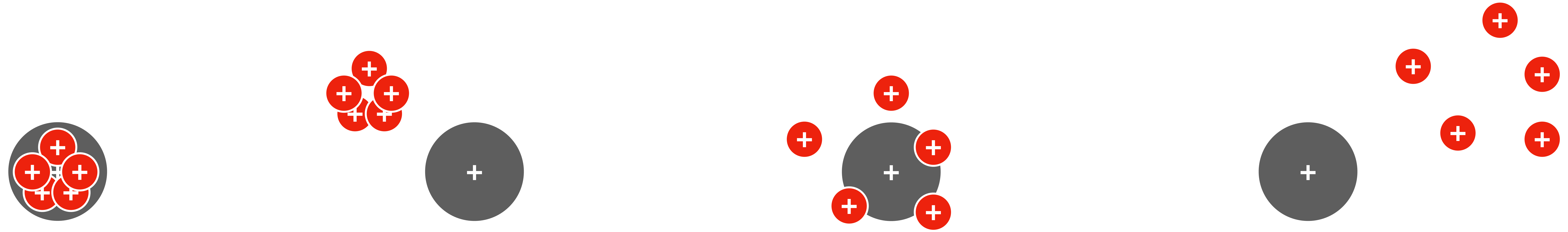
- Human-machine interaction
- Healthcare
- Education
- Digital Humanities
  - Study of human behaviour in specially constructed situations
  - Study of human spatial navigation and perception
  - Study of human communication
  - Study of human perception of information (e.g. via reading)

(Skulmowski et al. 2014; Sonntag et al. 2015; Lohr et al. 2019; Jogeshwar et al. 2020; Imaoka et al. 2020; Mirault et al. 2020; Ryabinin et al. 2021)

Eye trackers built in VR head-mounted displays have

low sampling rate
low accuracy
low precision

→ **Uncertainty of gaze data**

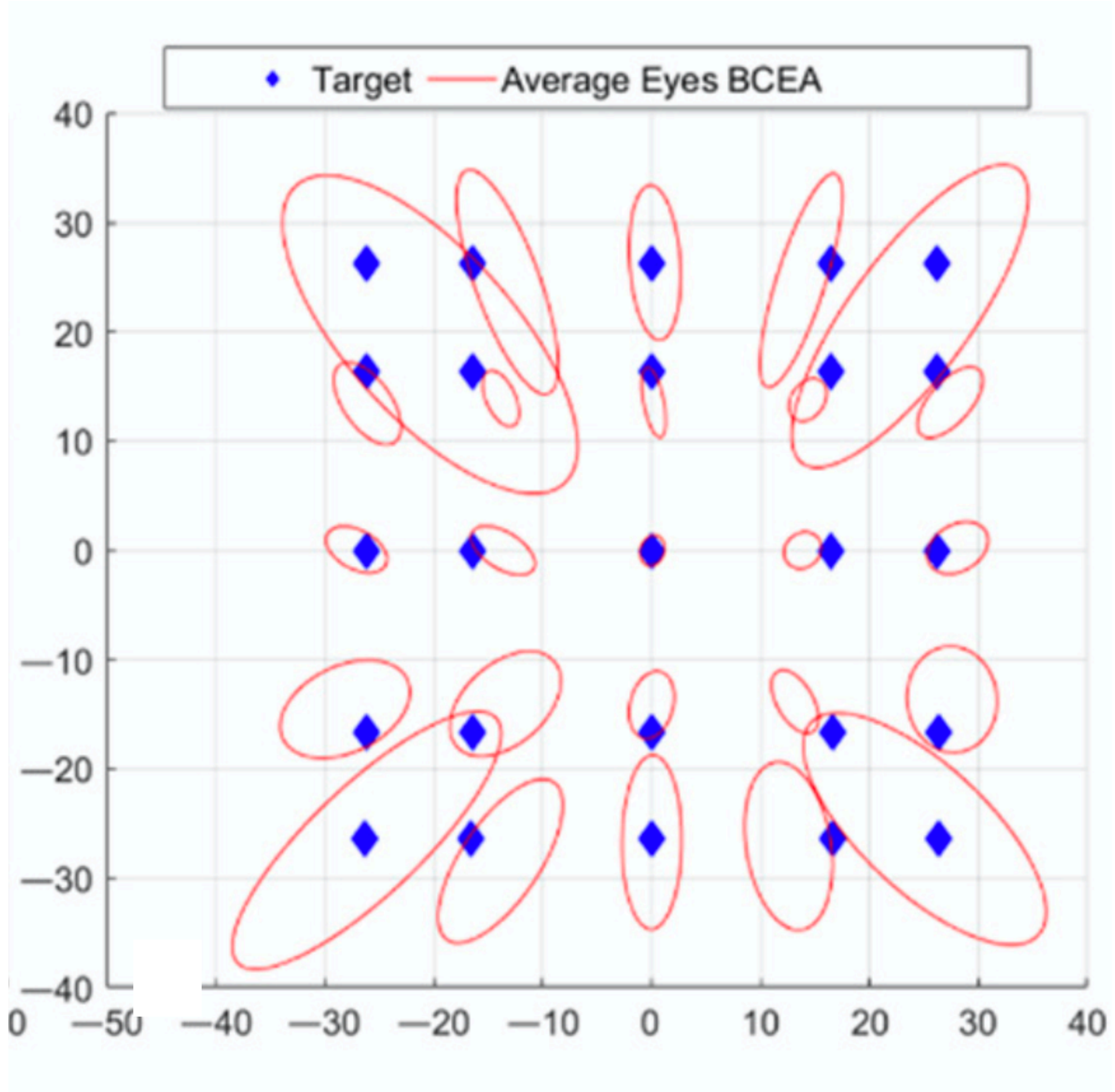


Good accuracy, Good precision | Bad accuracy, Good precision | Good accuracy, Bad precision | Bad accuracy Bad precision

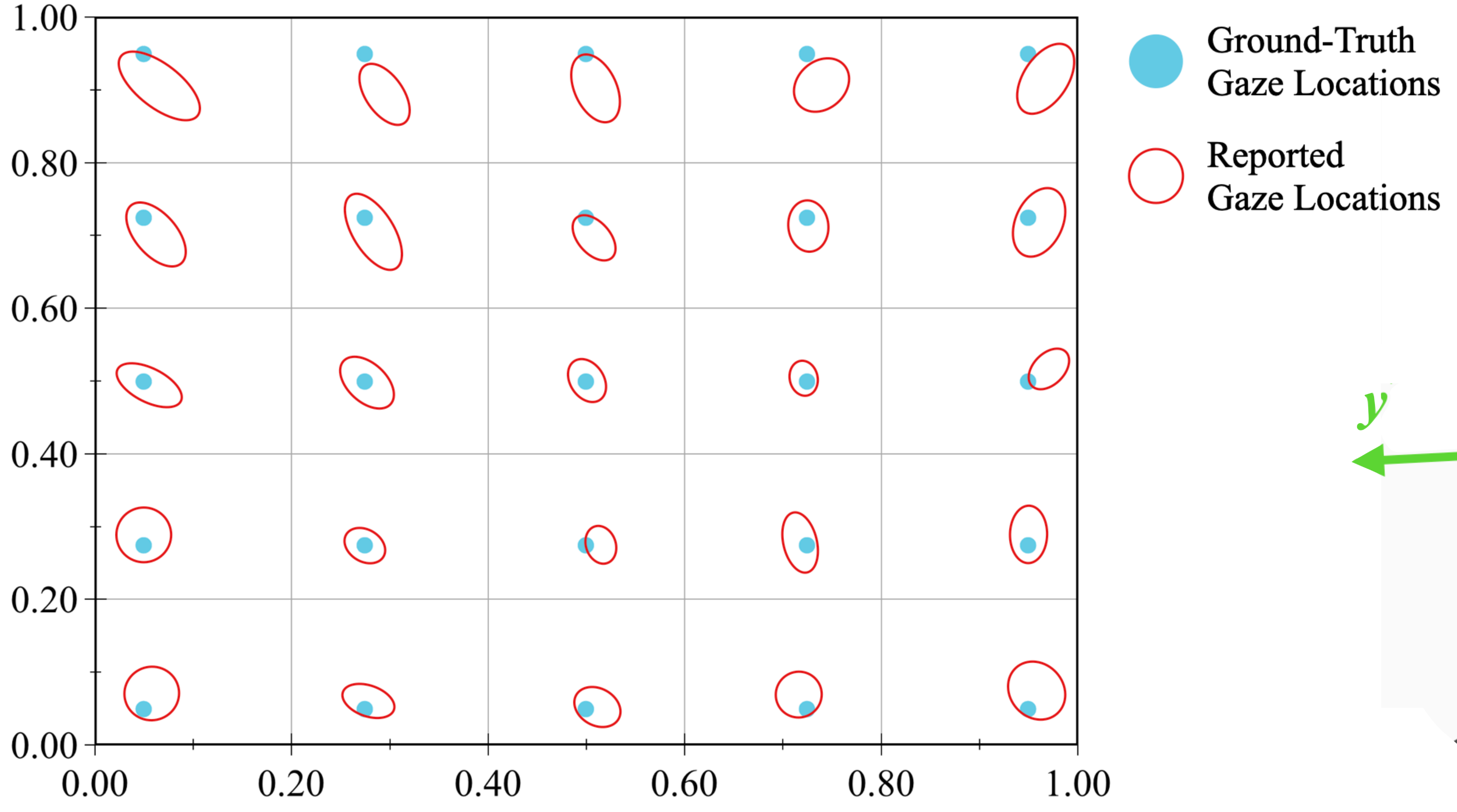
- Ground-truth gaze position
- Reported gaze position

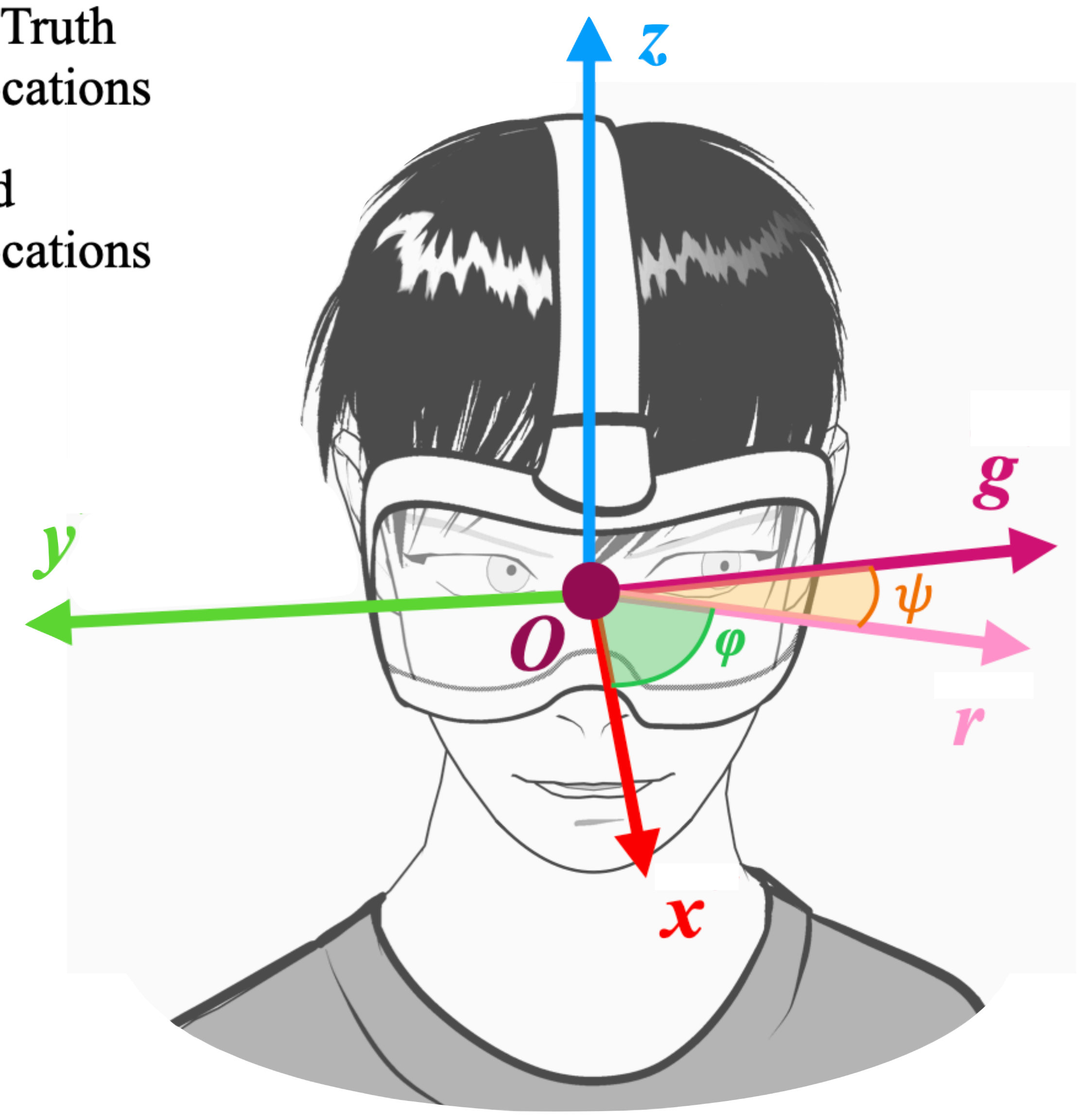
(Binaee et al., 2016; Sipatchin et al., 2021; Drewes et al. 2019)

Accuracy and precision drop when the user looks to the side from their forward direction



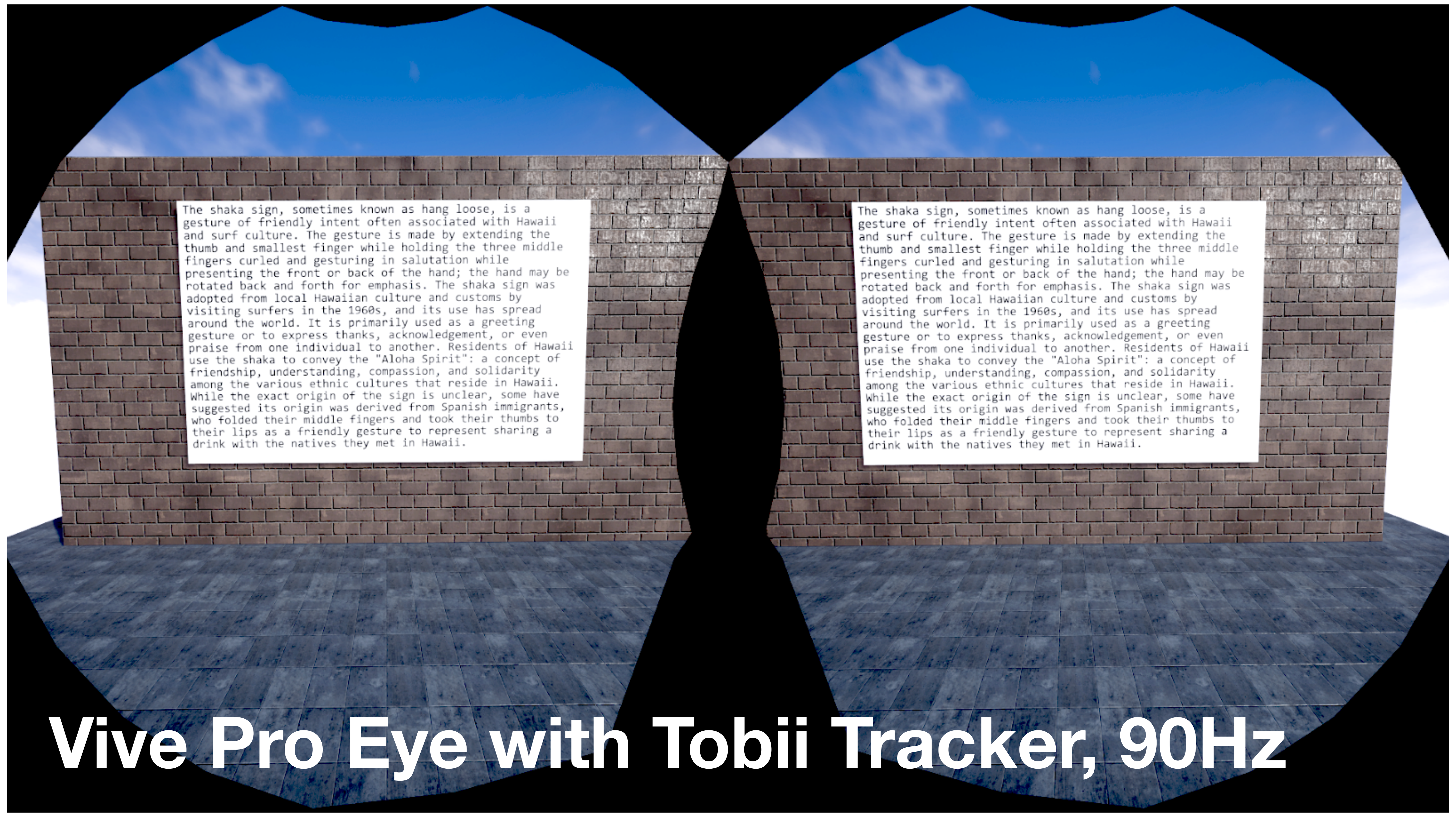
(Sipatchin et al., 2021)

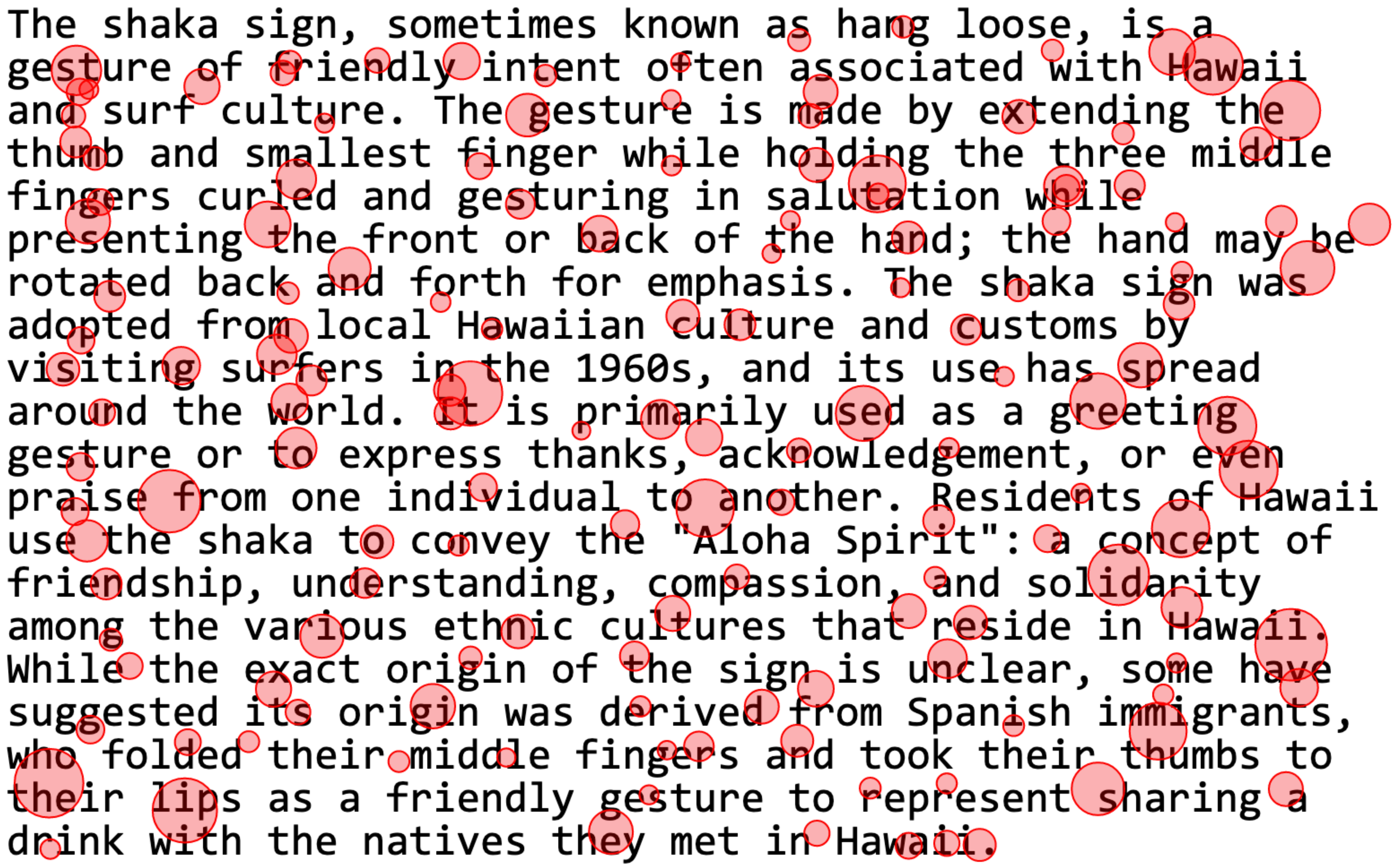




Our observations align with other research groups

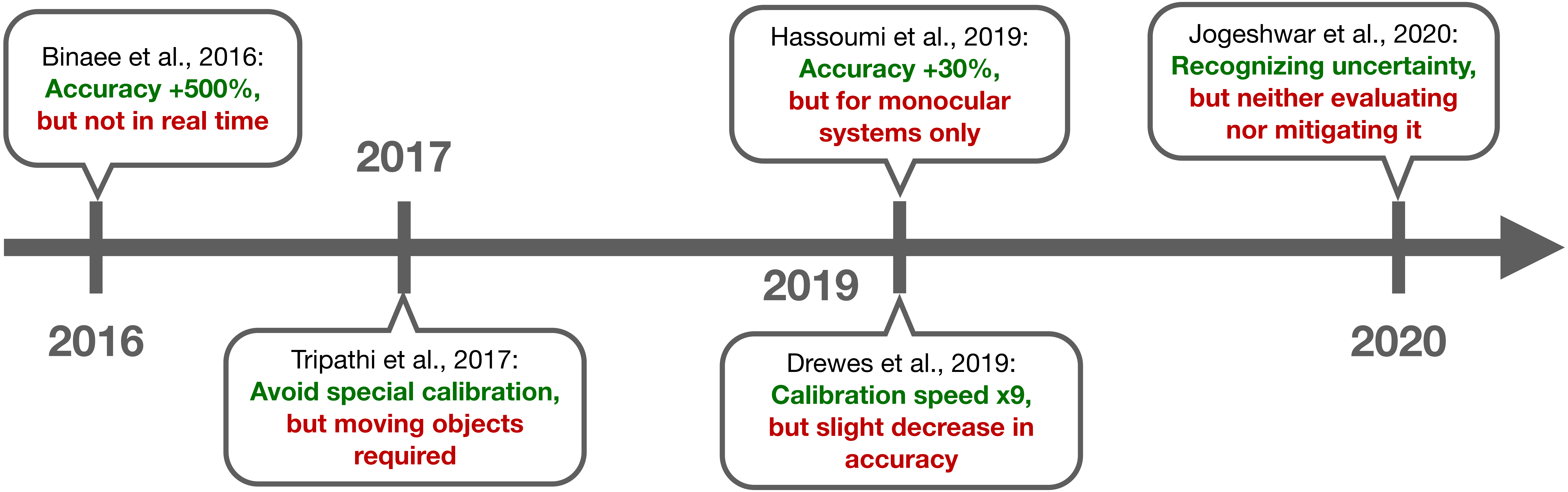
Our study of reading process



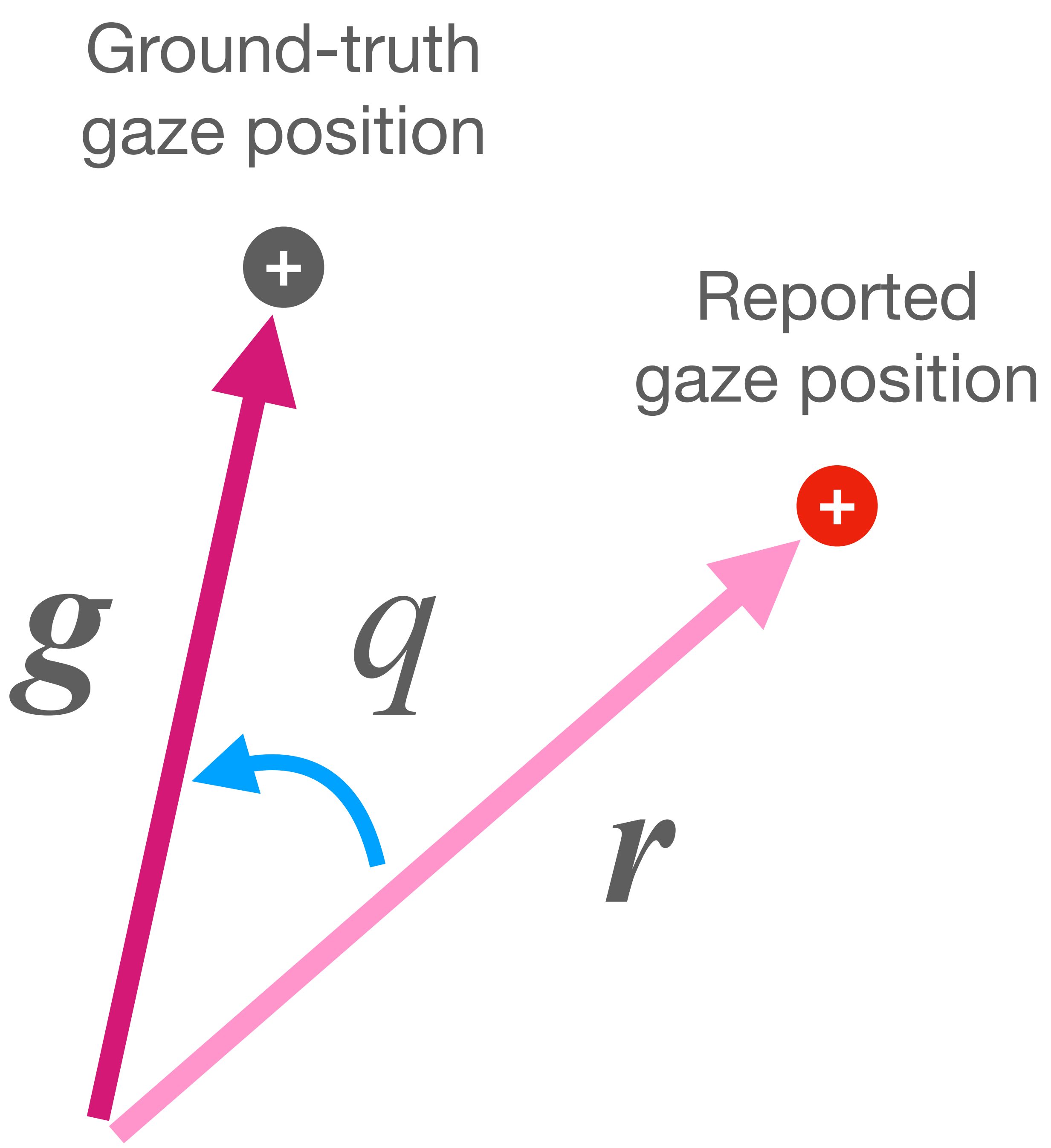


Angular error of gaze positions

Related Work: Uncertainty Mitigation



Proposed Quaternion-Based Uncertainty Model



Uncertainty representation quaternion

Reported gaze direction

Ground-truth gaze direction

$$q = \begin{cases} \{\boldsymbol{r} \cdot \boldsymbol{g} + 1, \boldsymbol{r} \times \boldsymbol{g}\}, & \boldsymbol{r} \cdot \boldsymbol{g} \neq -1 \\ \{0, \quad \boldsymbol{u}\}, \quad \boldsymbol{u} \cdot \boldsymbol{r} = 0, & \boldsymbol{r} \cdot \boldsymbol{g} = -1 \end{cases}$$

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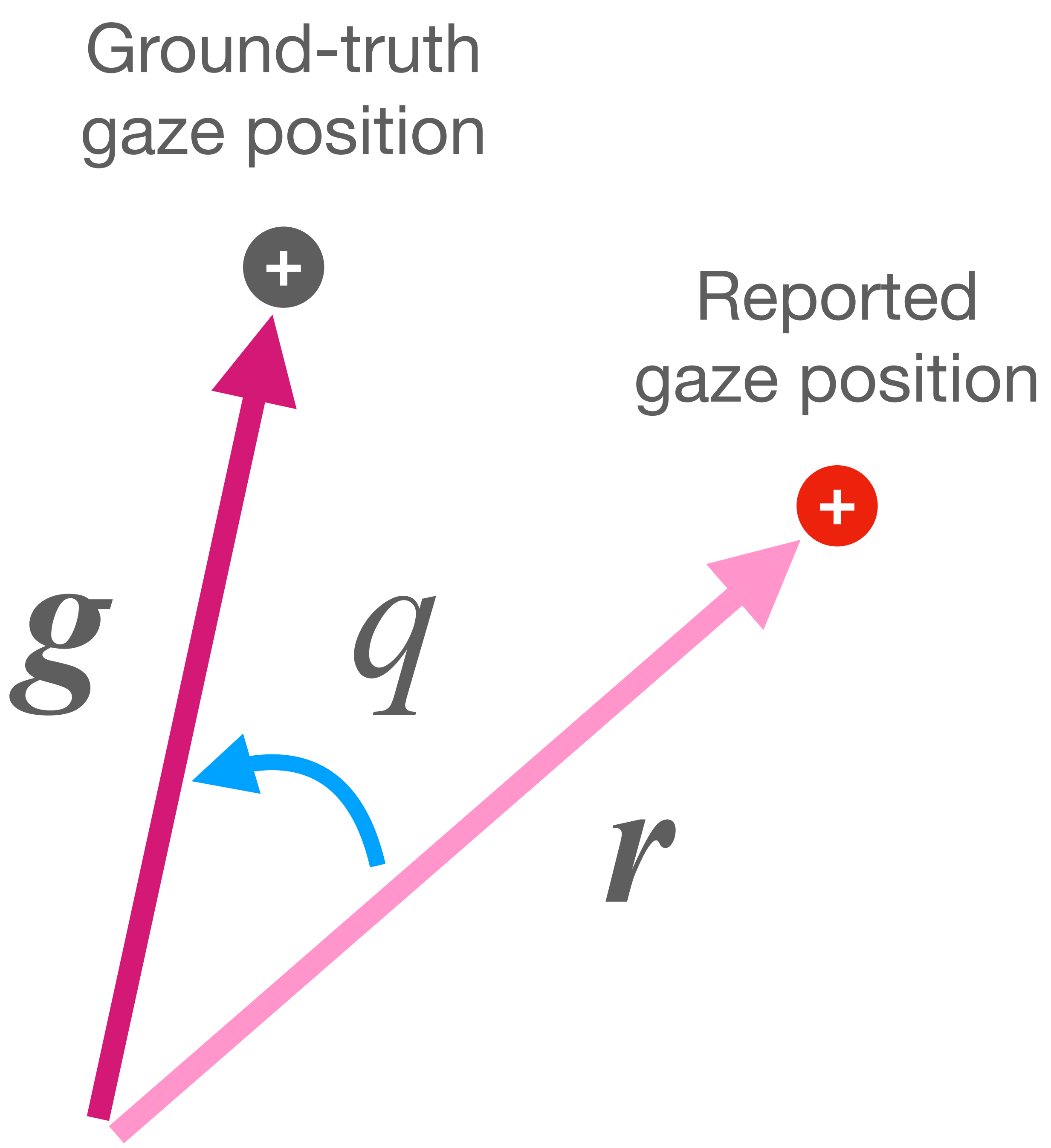

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$$q_{\boldsymbol{r} \to \boldsymbol{g}} = \frac{q}{|q|}$$ — Quaternion normalization

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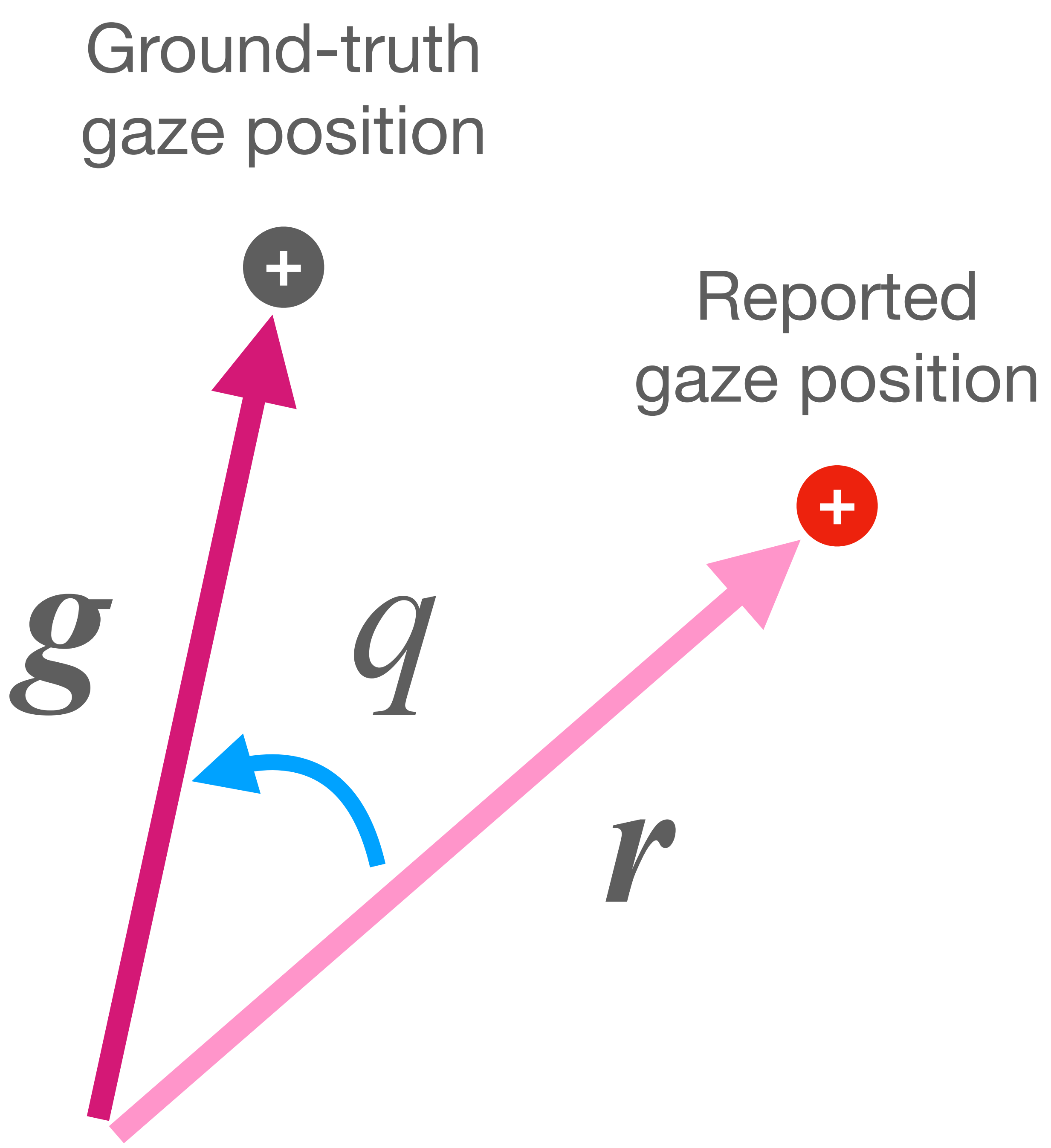

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$$\boldsymbol{g} = q_{\boldsymbol{r} \to \boldsymbol{g}} \ \boldsymbol{r} \ q^{*}_{\boldsymbol{r} \to \boldsymbol{g}}$$ — Angular error correction

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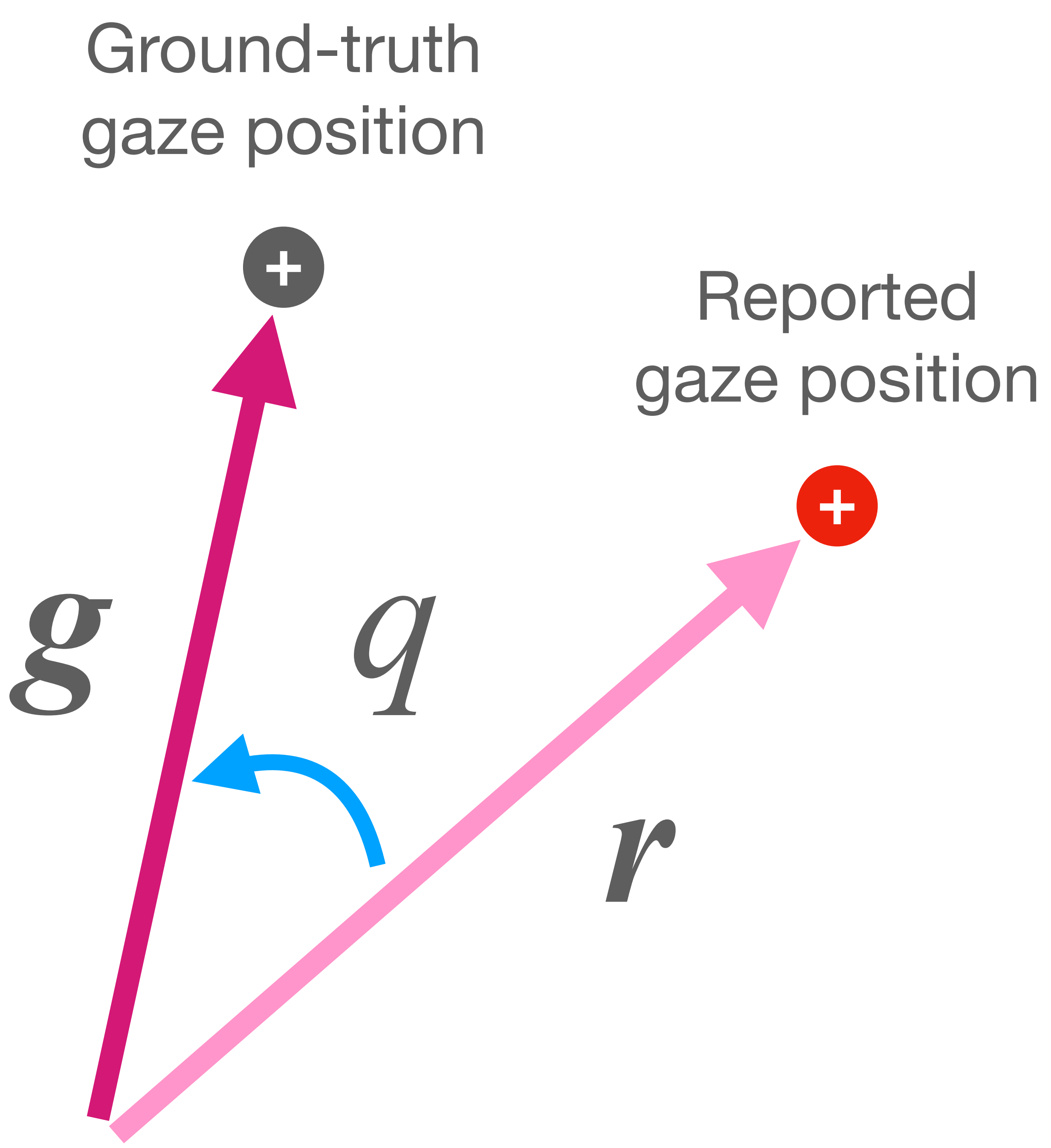

Uncertainty representation quaternion; Reported gaze direction; Ground-truth gaze direction

$$q = \begin{cases} \{\boldsymbol{r}\cdot\boldsymbol{g}+1,\ \boldsymbol{r}\times\boldsymbol{g}\}, & \boldsymbol{r}\cdot\boldsymbol{g}\neq -1 \\ \{0,\ \boldsymbol{u}\}, & \boldsymbol{u}\cdot\boldsymbol{r}=0,\ \ \boldsymbol{r}\cdot\boldsymbol{g}=-1 \end{cases}$$

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$$\mathrm{CF}(\boldsymbol{r}) = \mathrm{Re}(q_{\boldsymbol{r}\to\boldsymbol{g}})$$ — Certainty factor

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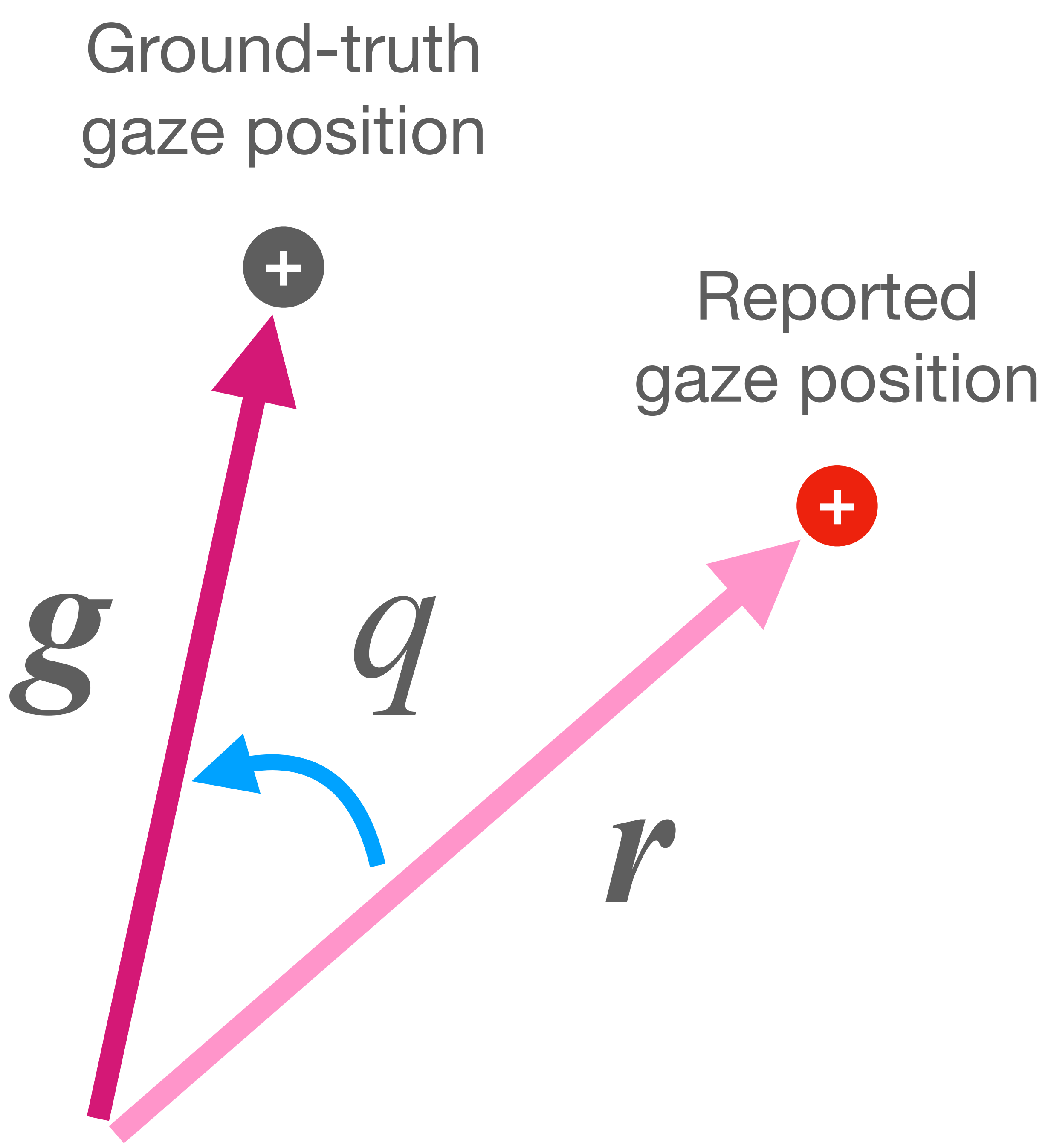

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$$q_{\boldsymbol{r} \to \boldsymbol{g}} = \frac{q}{|q|}$$ — Quaternion normalization

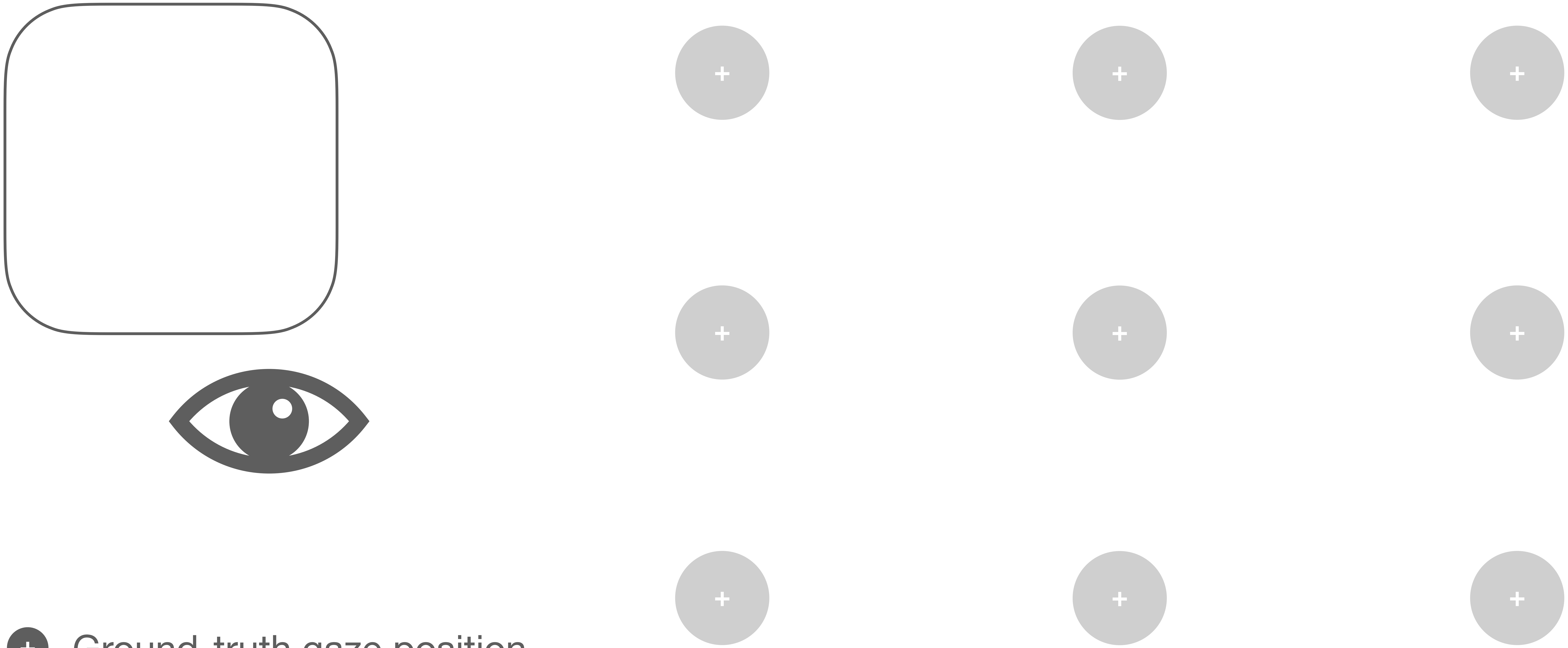
$$\boldsymbol{g} = q_{\boldsymbol{r} \to \boldsymbol{g}} \; \boldsymbol{r} \; q^*_{\boldsymbol{r} \to \boldsymbol{g}}$$ — Angular error correction

$$\mathrm{CF}(\boldsymbol{r}) = \mathrm{Re}(q_{\boldsymbol{r} \to \boldsymbol{g}})$$ — Certainty factor

$$\psi_{\boldsymbol{r}} = 2 \arccos\left(\mathrm{CF}(\boldsymbol{r})\right)$$ — Angular error assessment

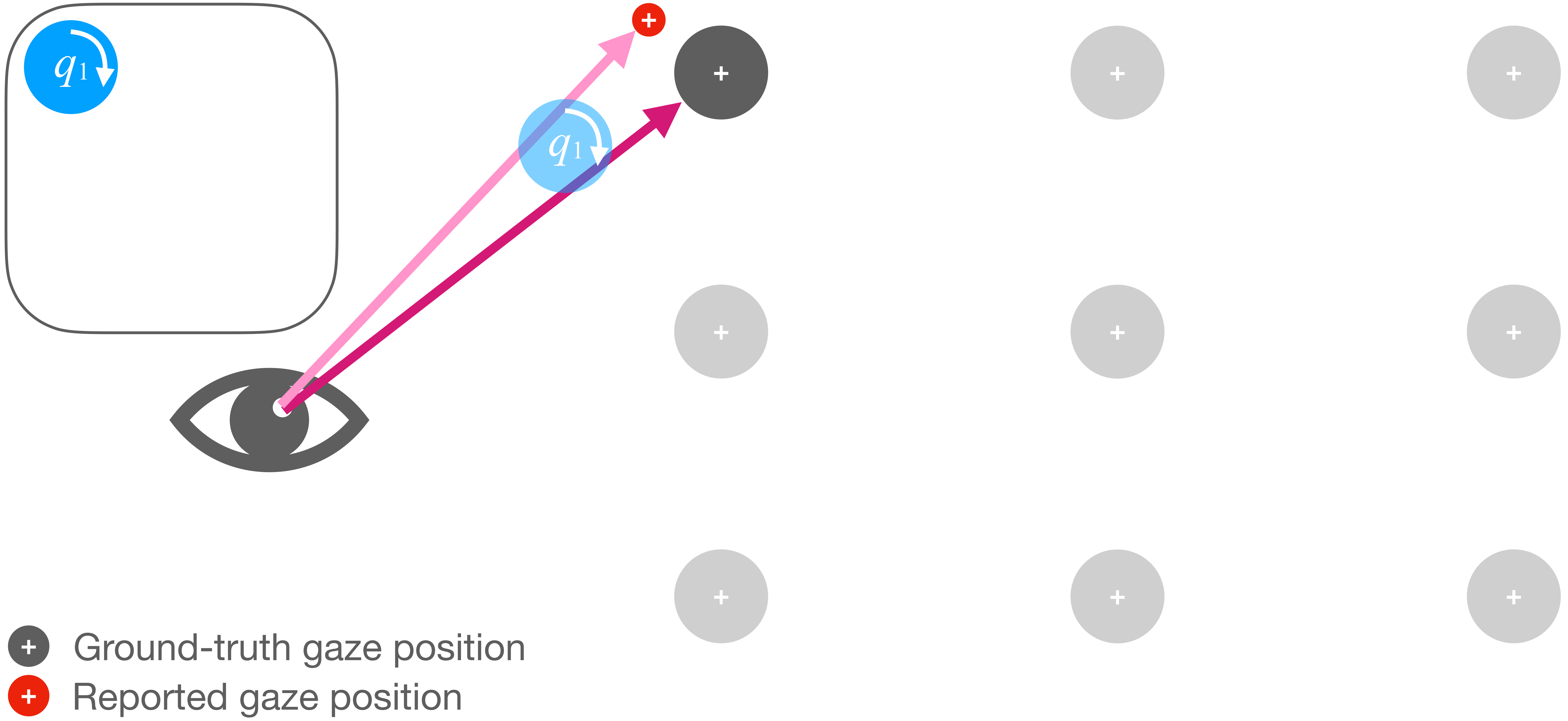
Proposed Uncertainty Mitigation Algorithm: Calibration

Reference quaternions



- Ground-truth gaze position
- Reported gaze position

Reference quaternions



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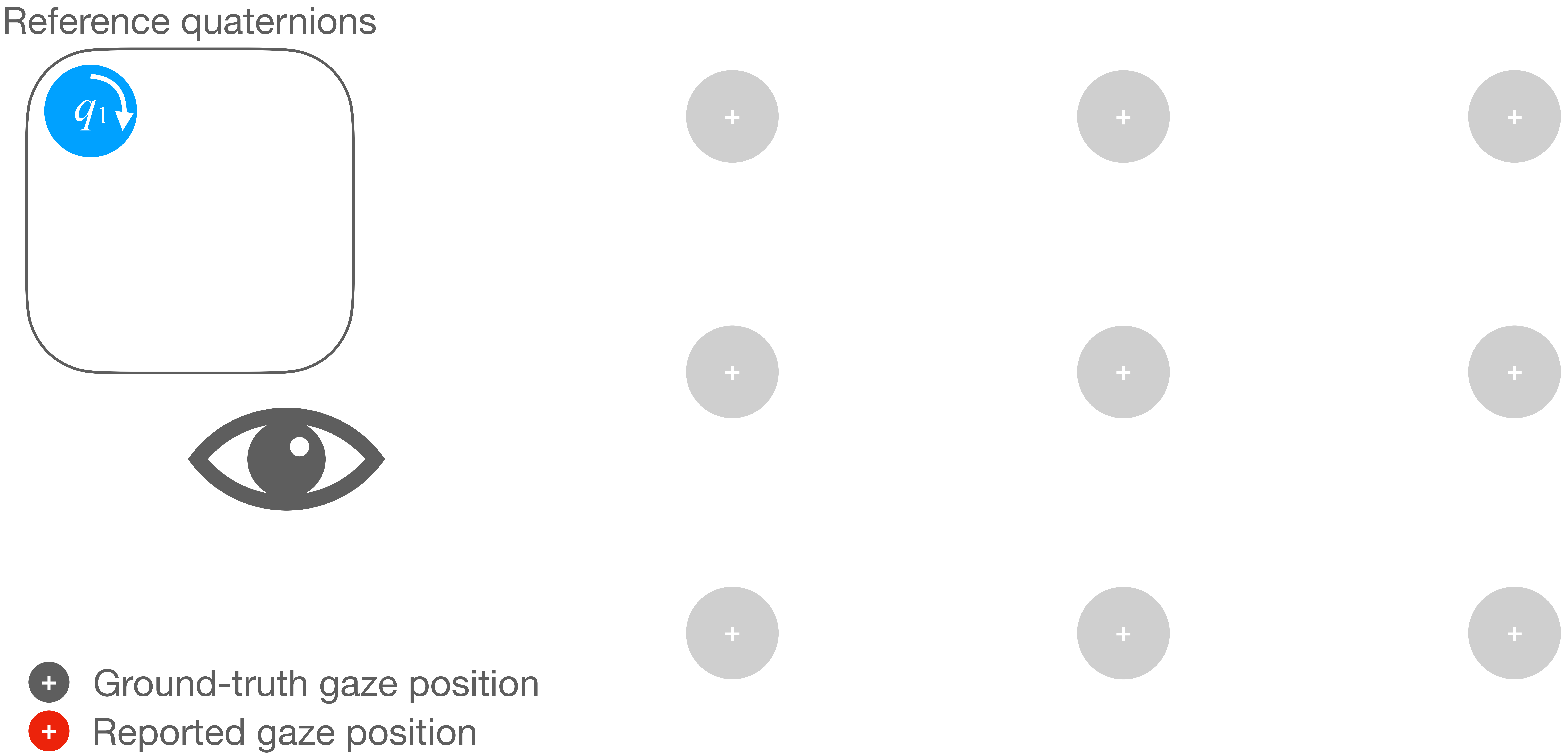
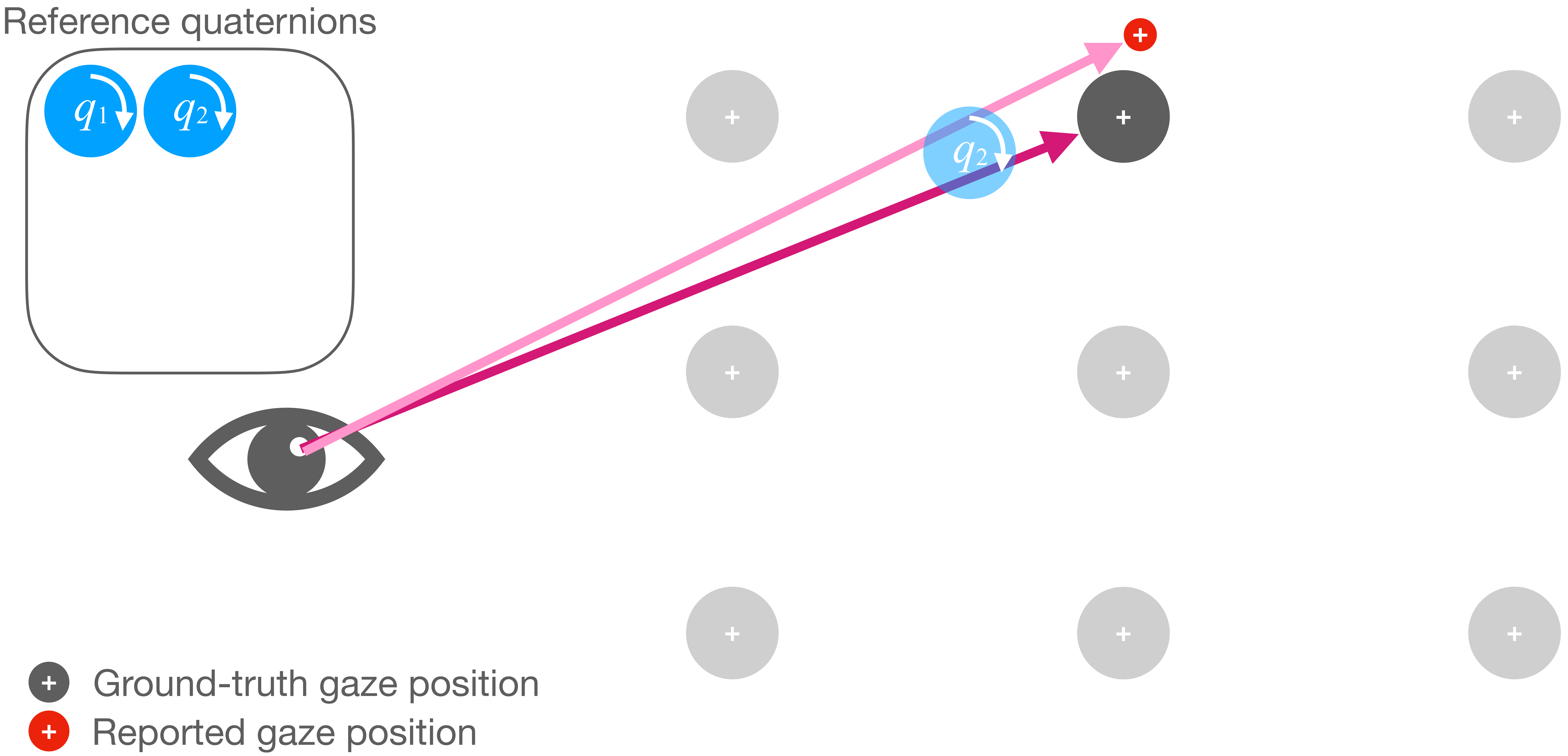
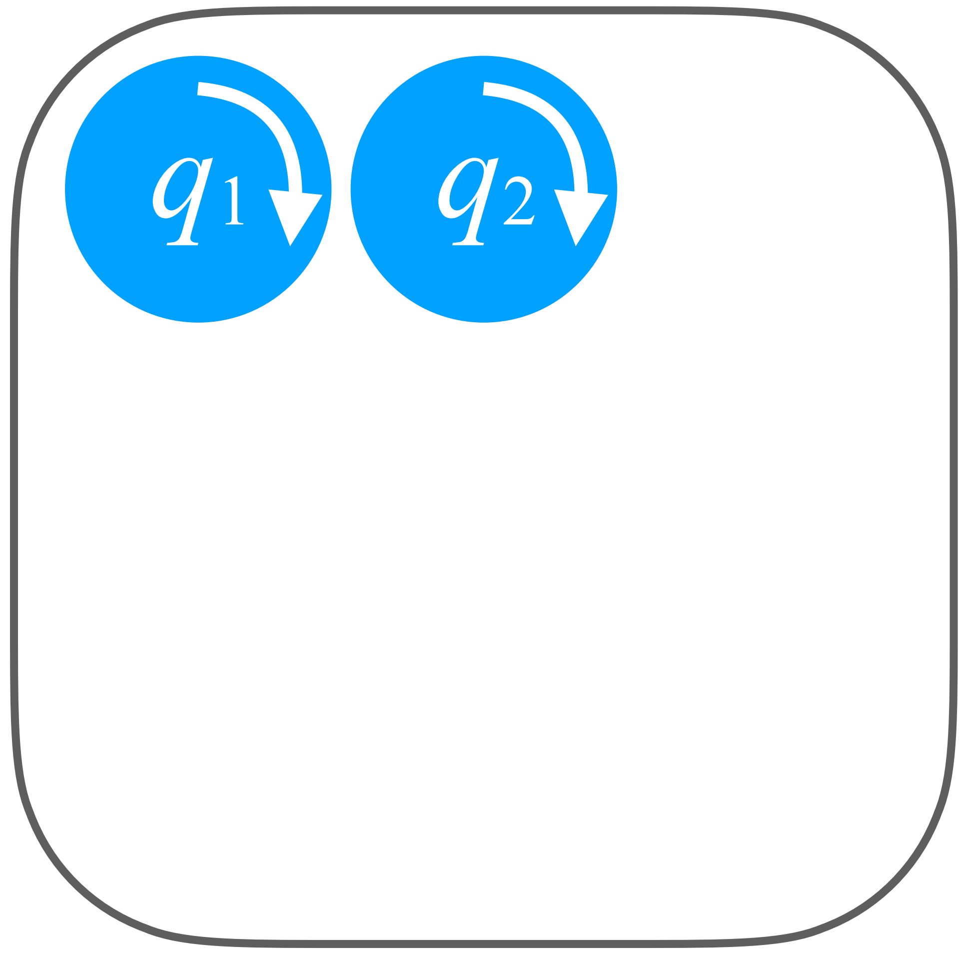
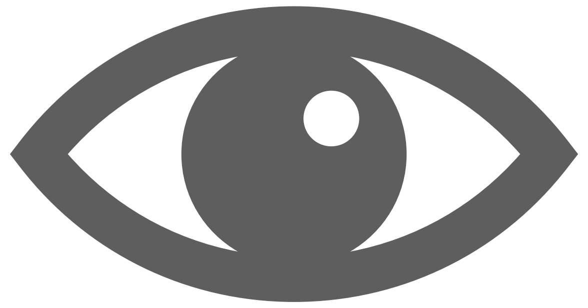



Reference quaternions
q_1
q_2
q_2
Ground-truth gaze position
Reported gaze position

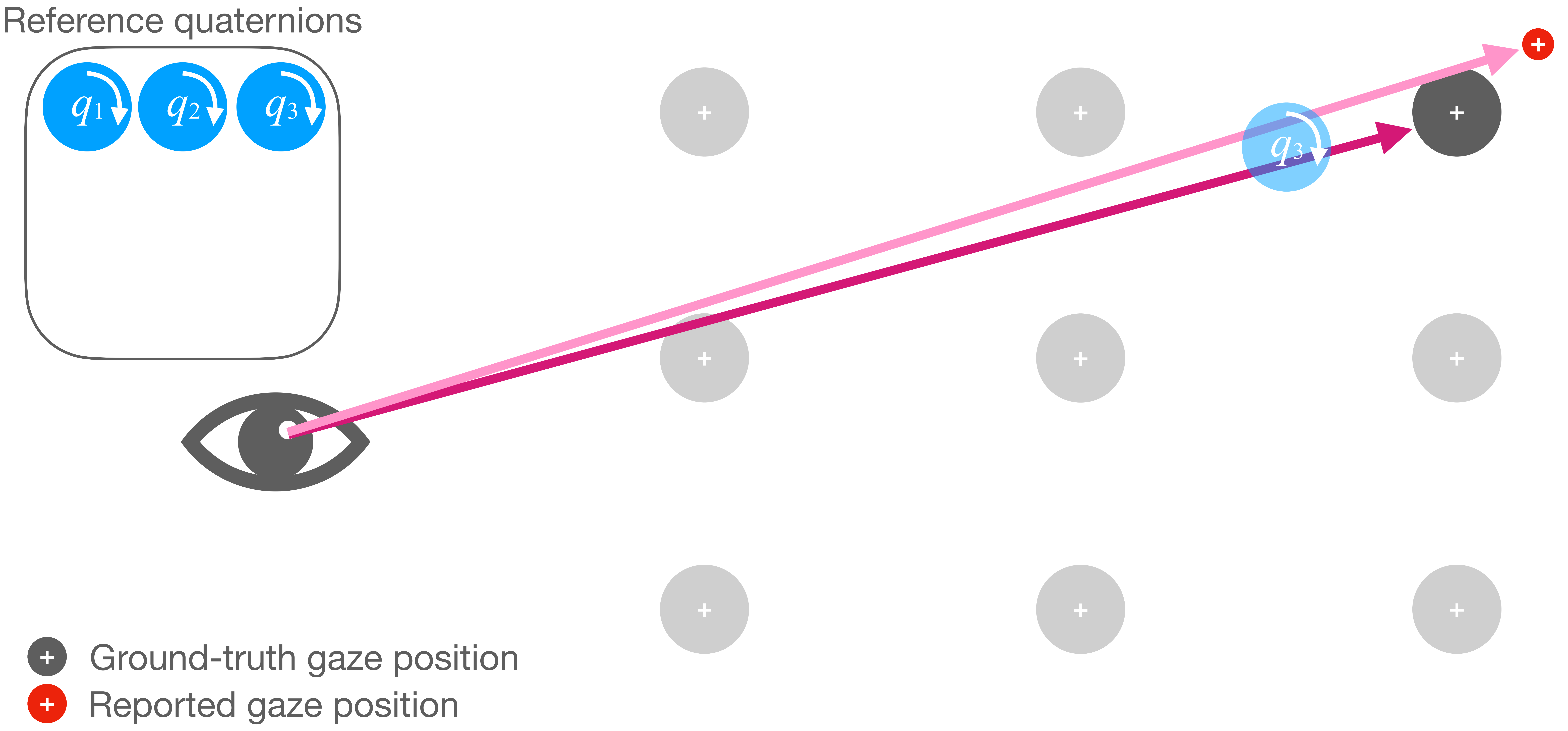
Reference quaternions



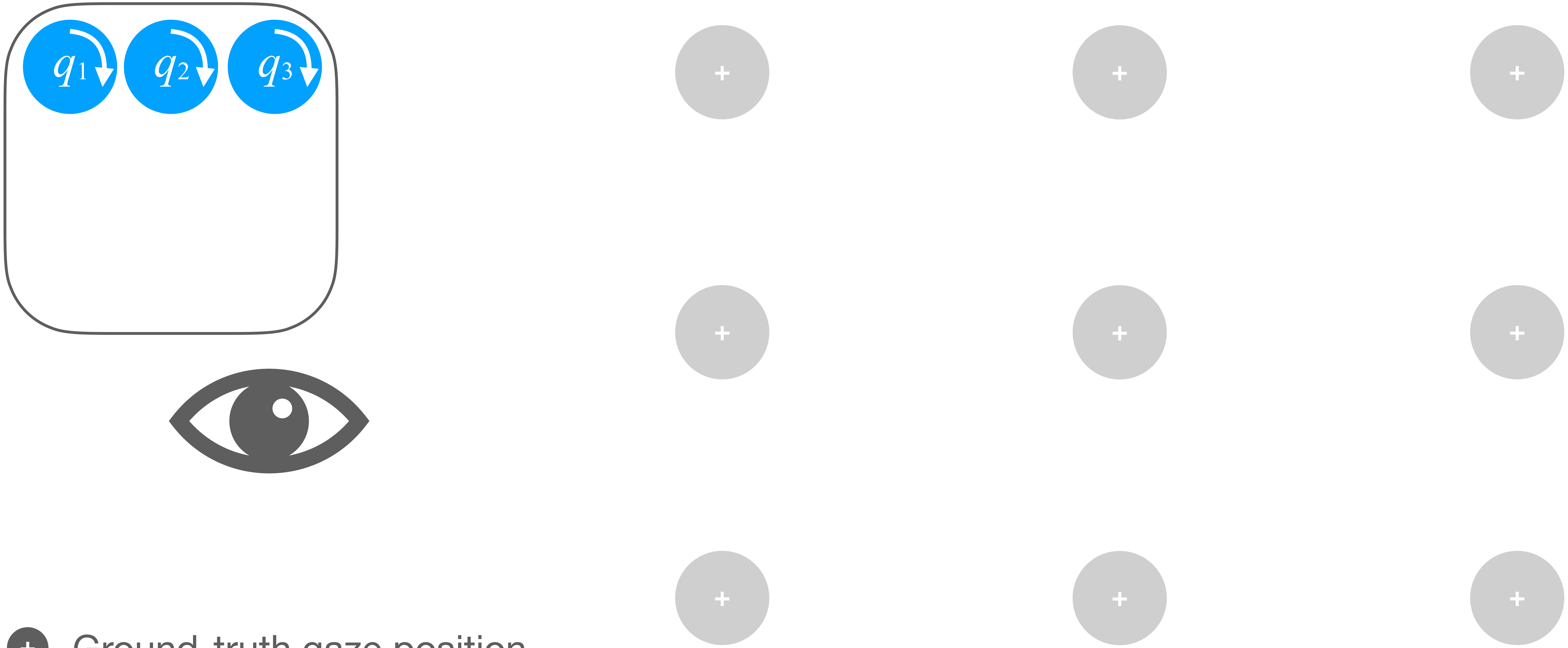


Ground-truth gaze position
Reported gaze position

Proposed Uncertainty Mitigation Algorithm: Calibration



Reference quaternions



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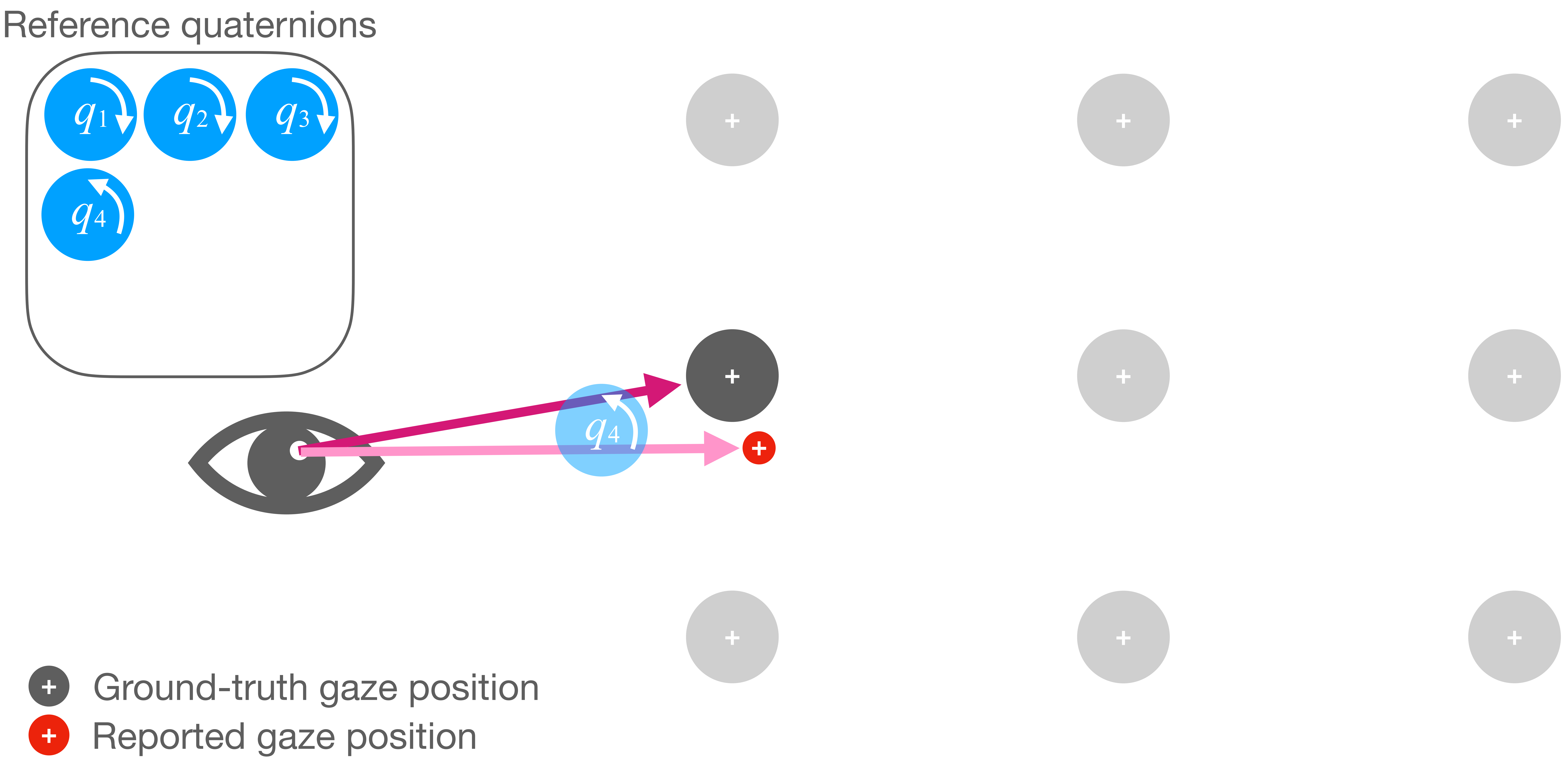
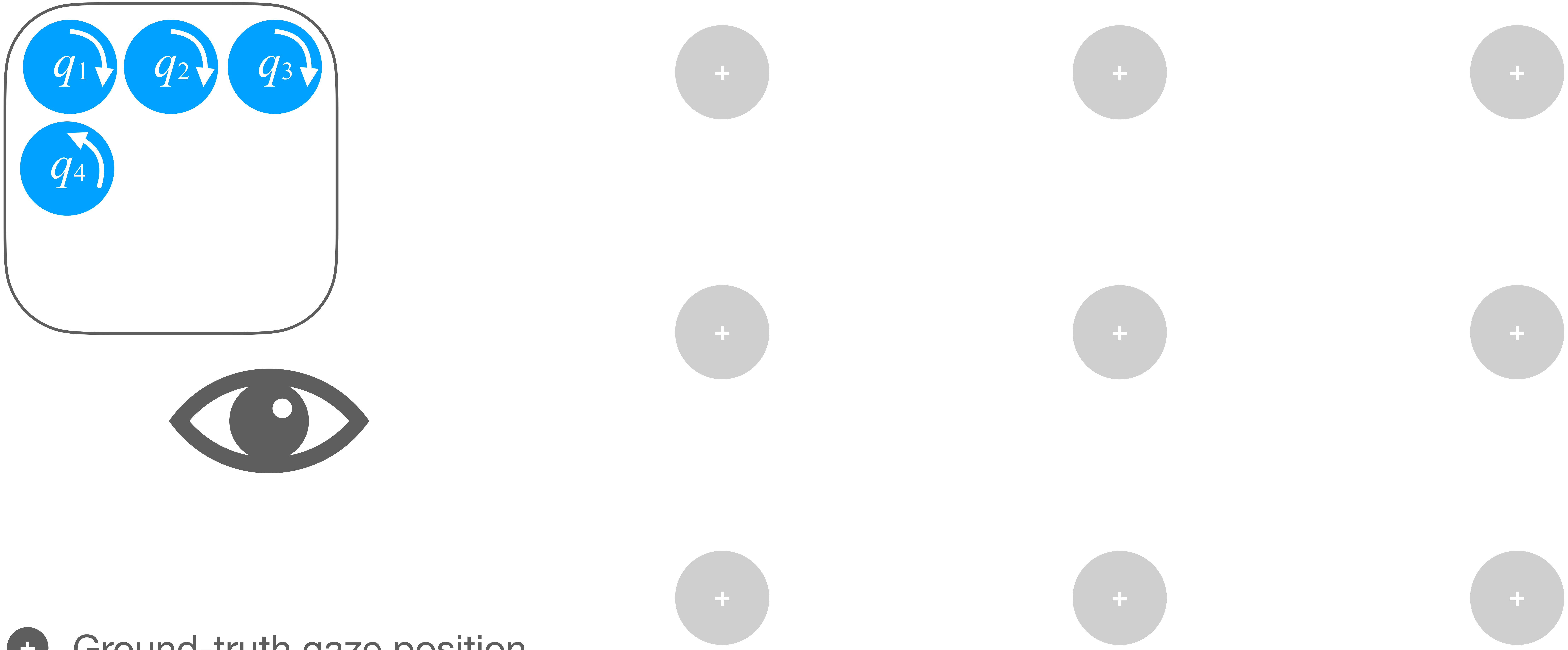

Reference quaternions
q1
q2
q3
q4
q4
Ground-truth gaze position
Reported gaze position

Reference quaternions



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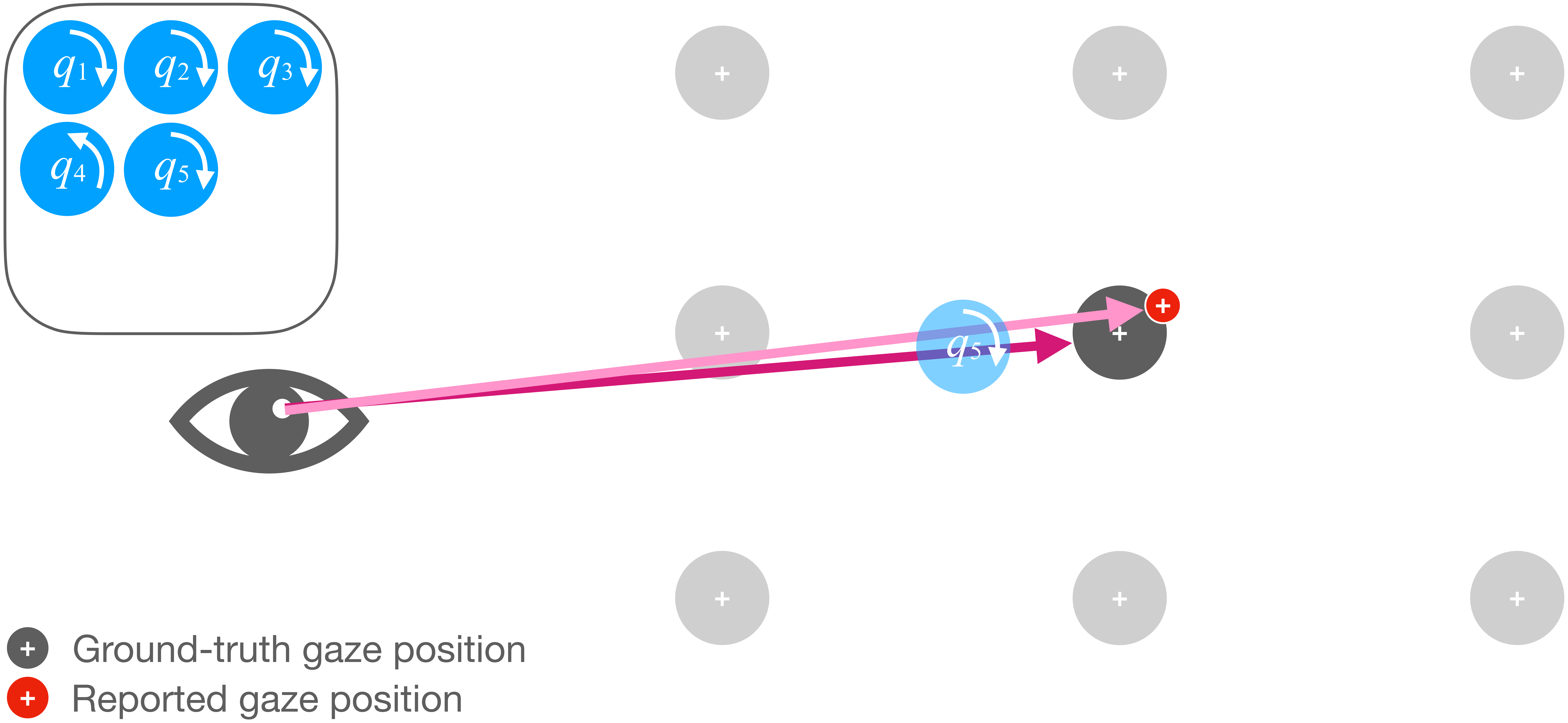
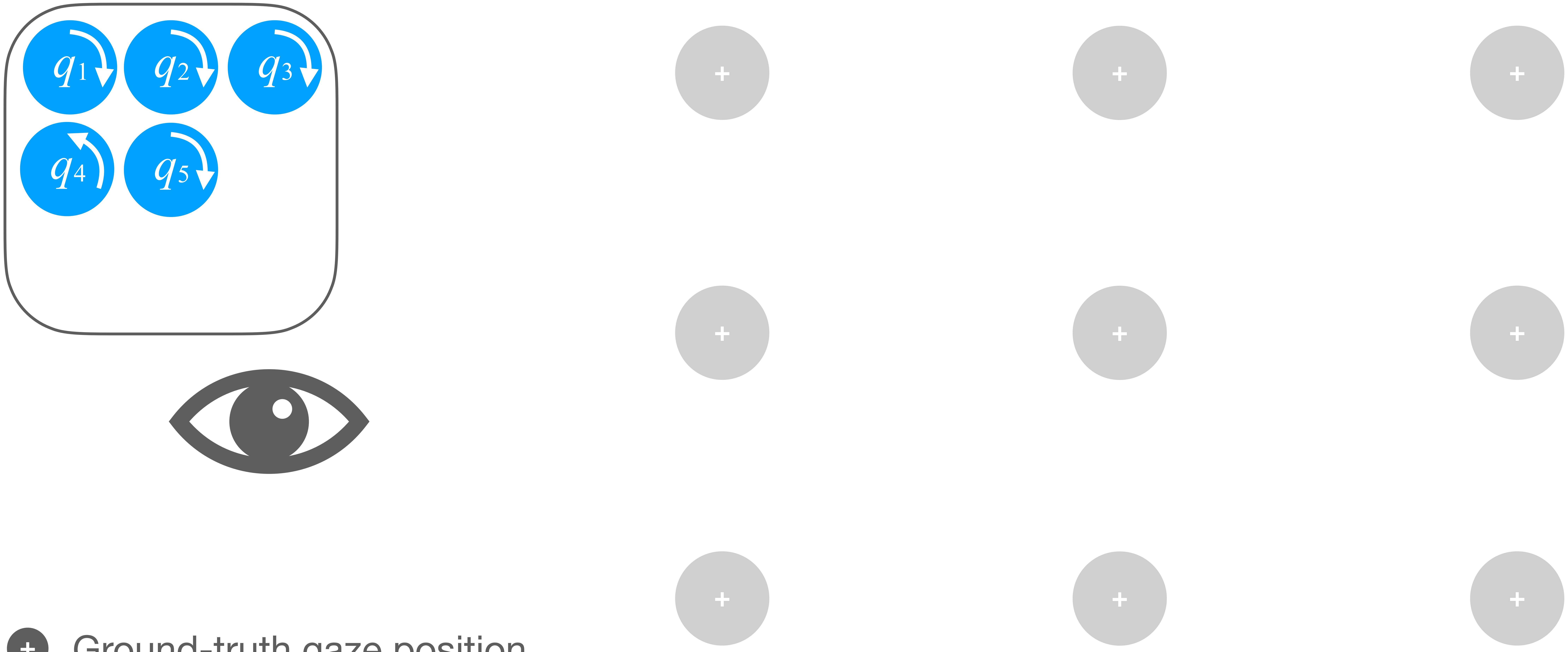
Proposed Uncertainty Mitigation Algorithm: Calibration

Reference quaternions



Reference quaternions

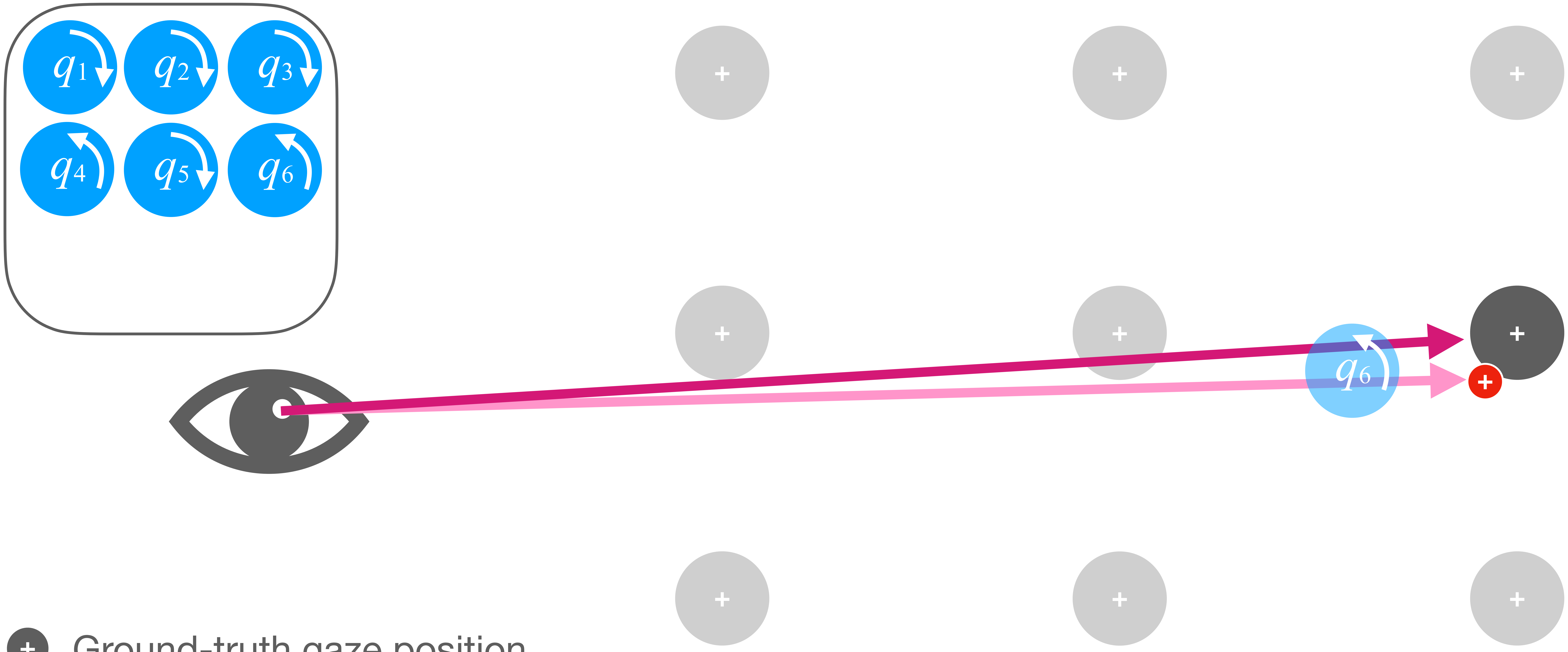


Ground-truth gaze position

Reported gaze position

Proposed Uncertainty Mitigation Algorithm: Calibration

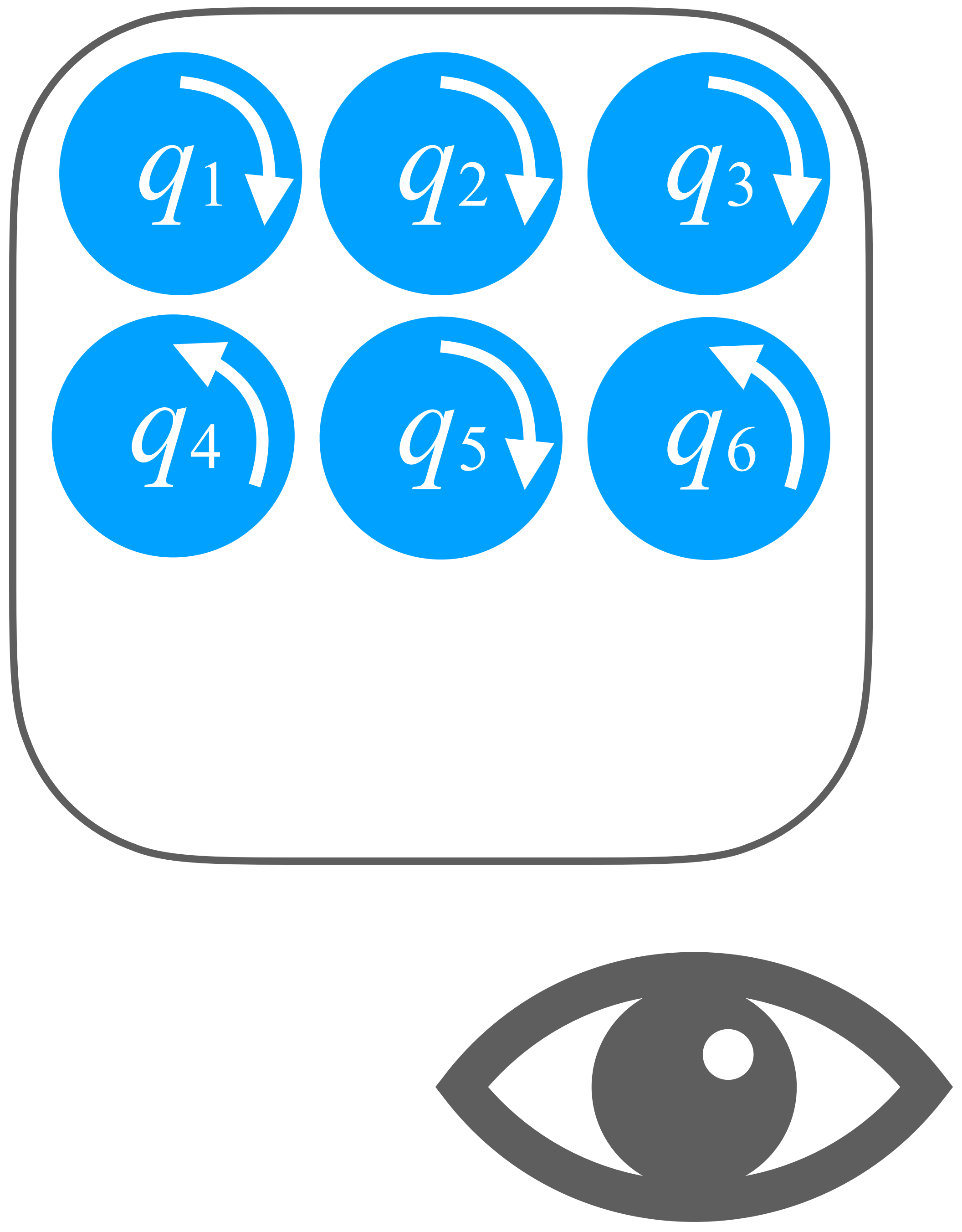
Reference quaternions



Ground-truth gaze position

Reported gaze position

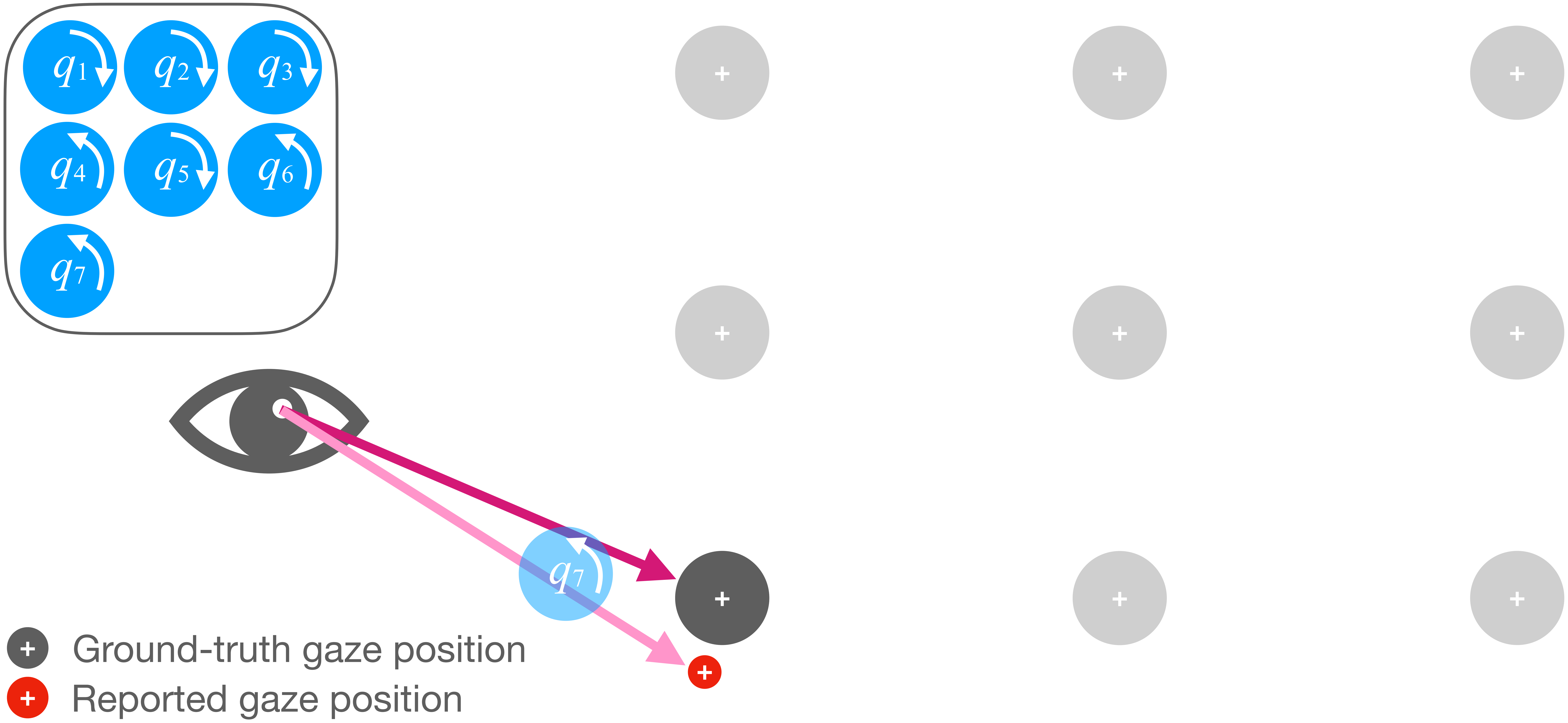
Reference quaternions



Ground-truth gaze position

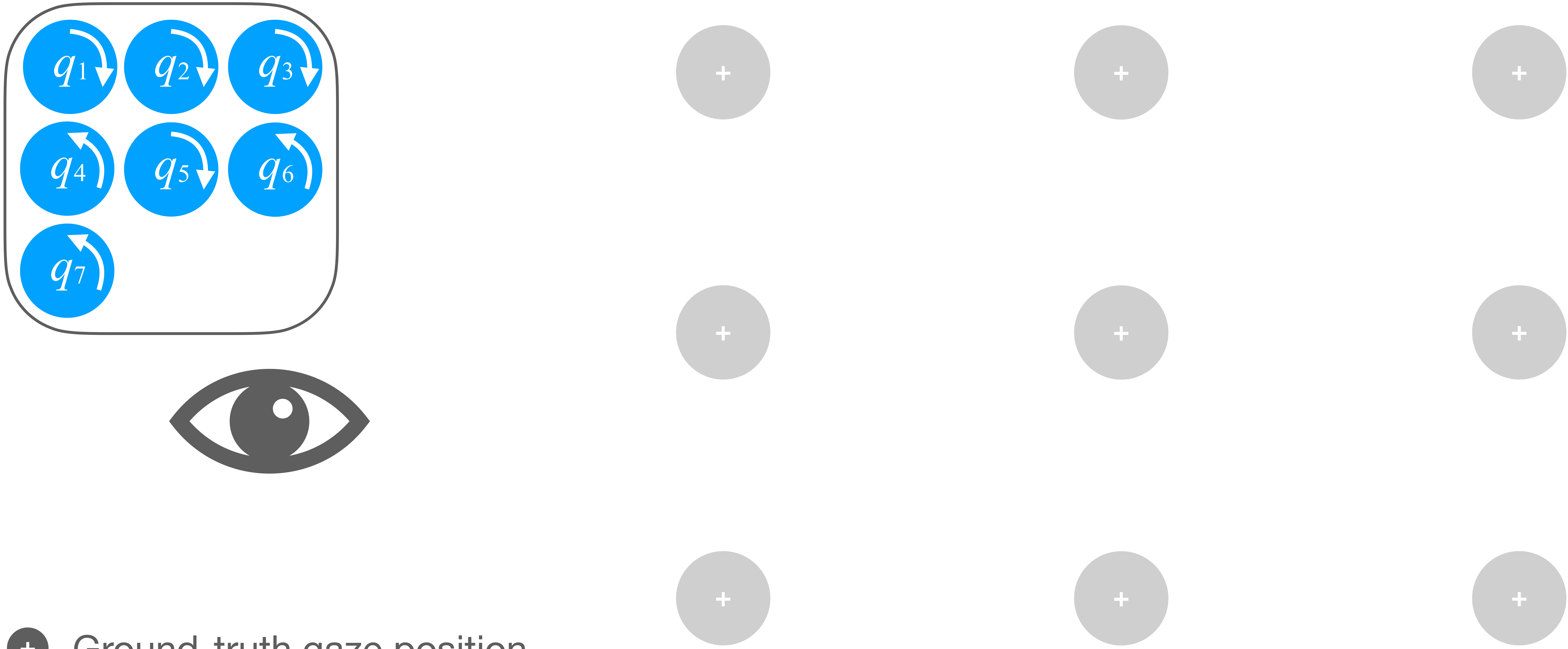
Reported gaze position

Reference quaternions



Proposed Uncertainty Mitigation Algorithm: Calibration

Reference quaternions



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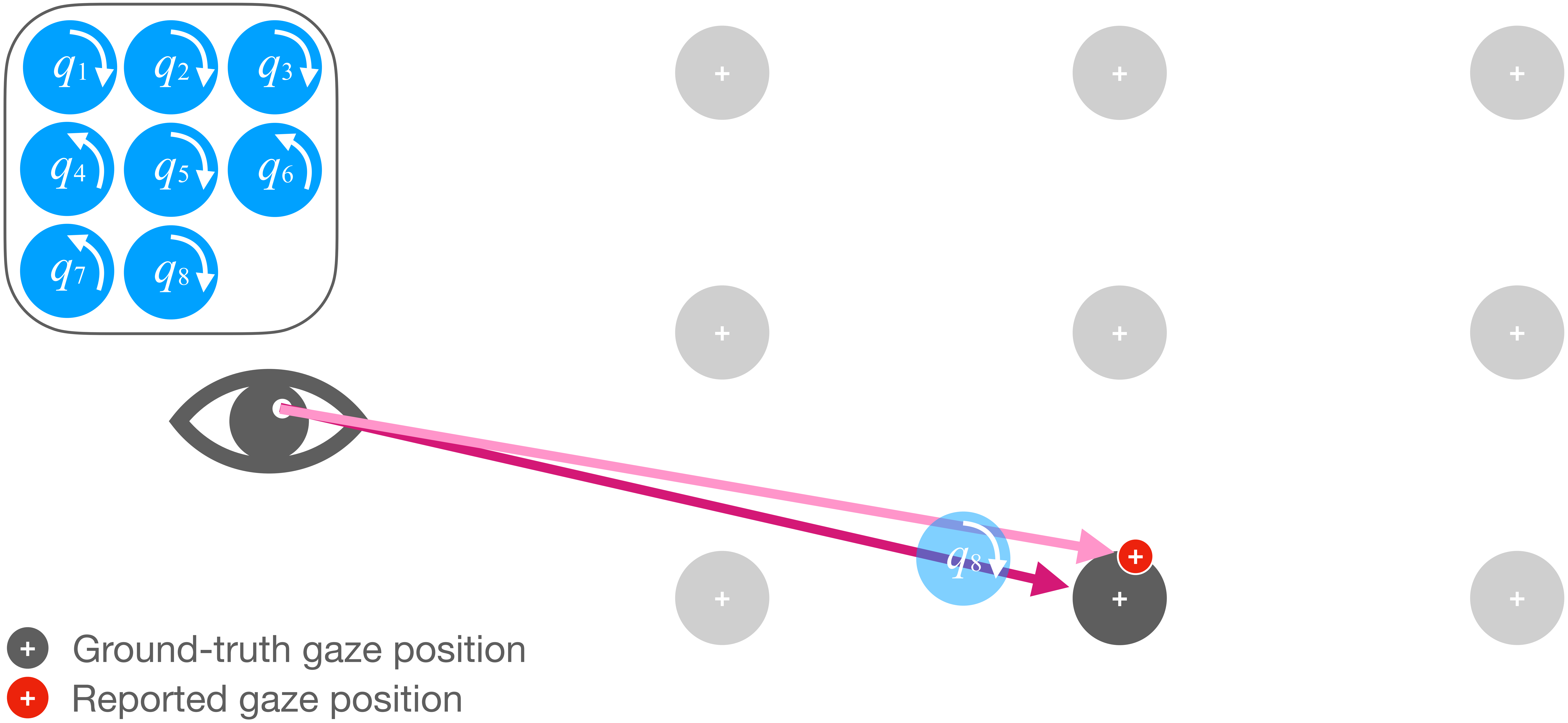
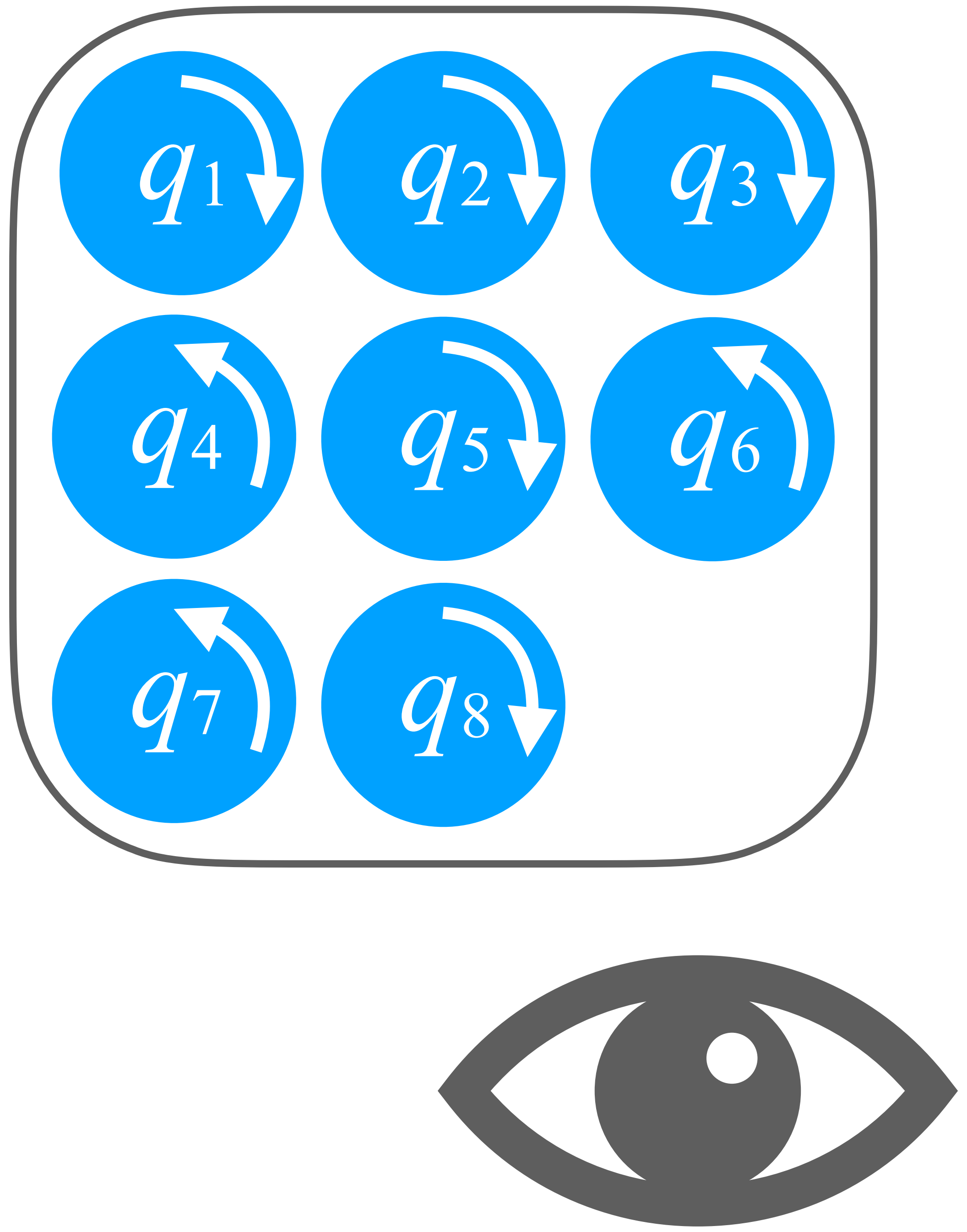
Proposed Uncertainty Mitigation Algorithm: Calibration

Reference quaternions



Proposed Uncertainty Mitigation Algorithm: Calibration

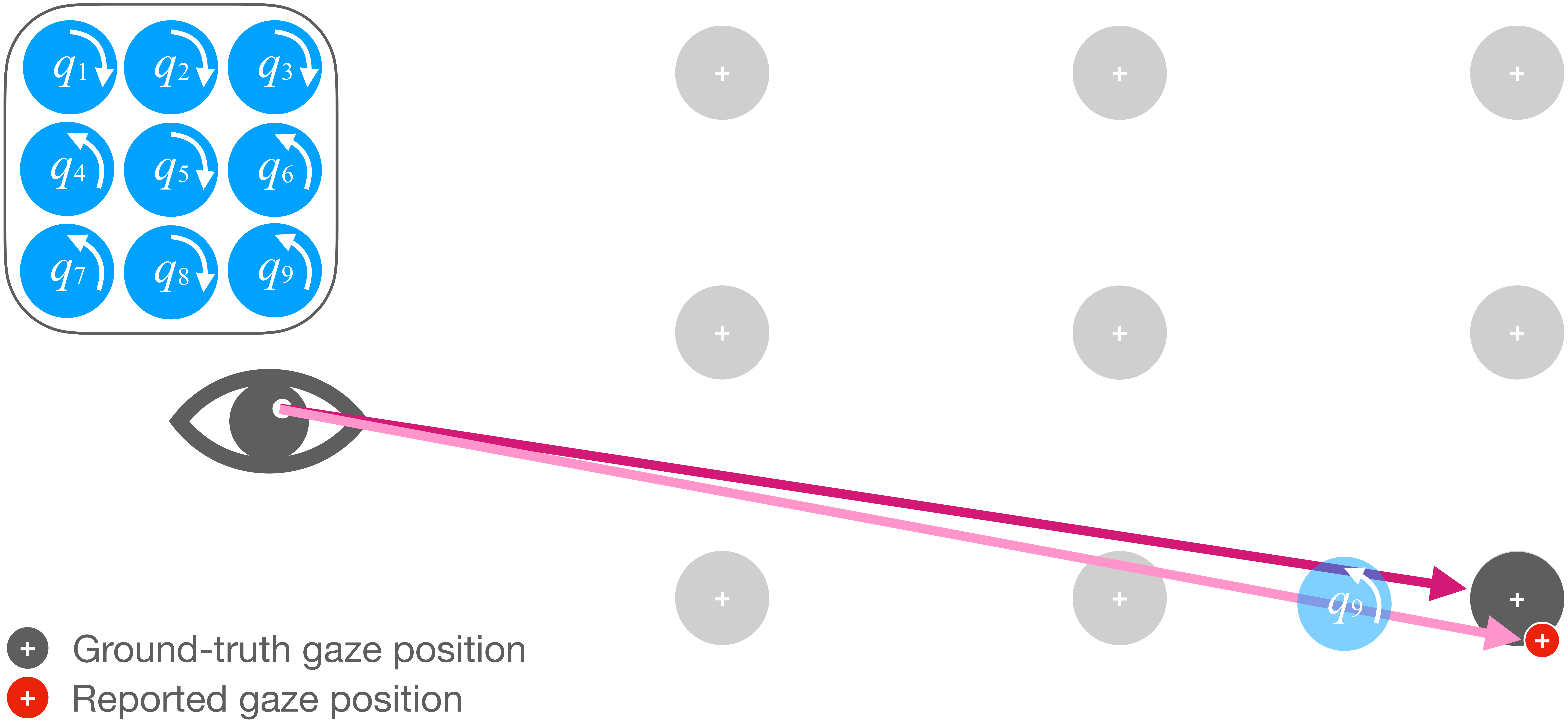
Reference quaternions



- Ground-truth gaze position
- Reported gaze position

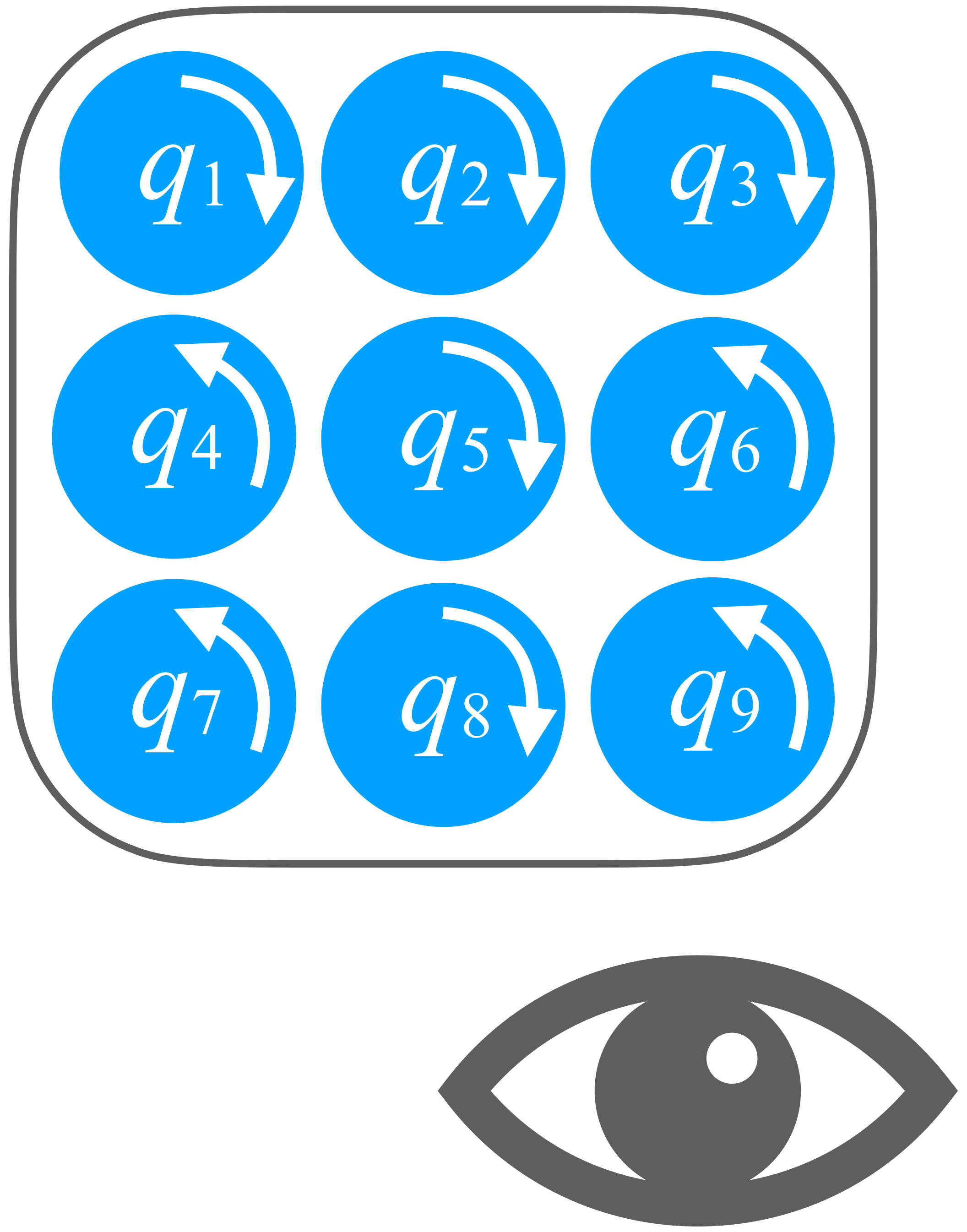
Proposed Uncertainty Mitigation Algorithm: Calibration

Reference quaternions

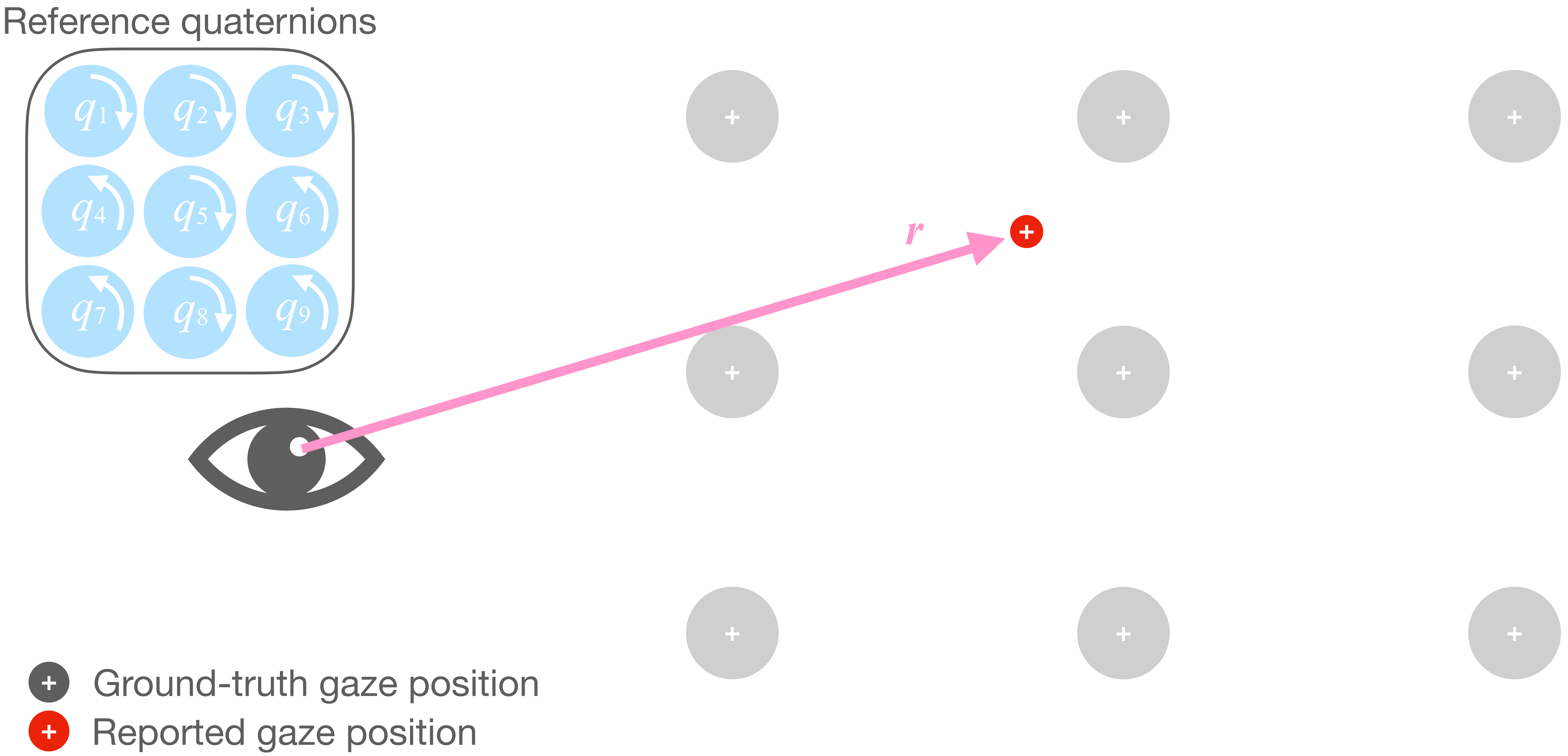


Proposed Uncertainty Mitigation Algorithm: Calibration

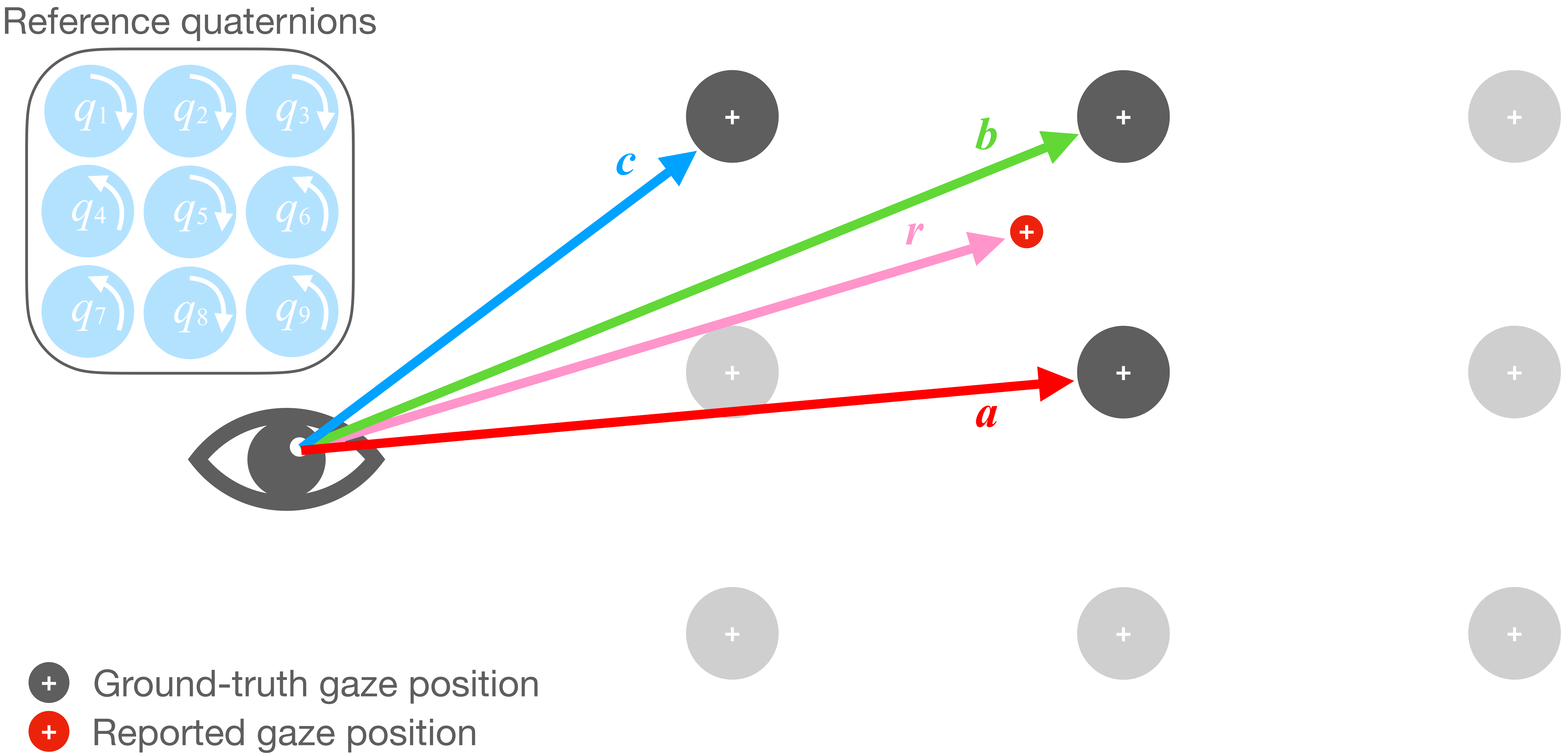
Reference quaternions

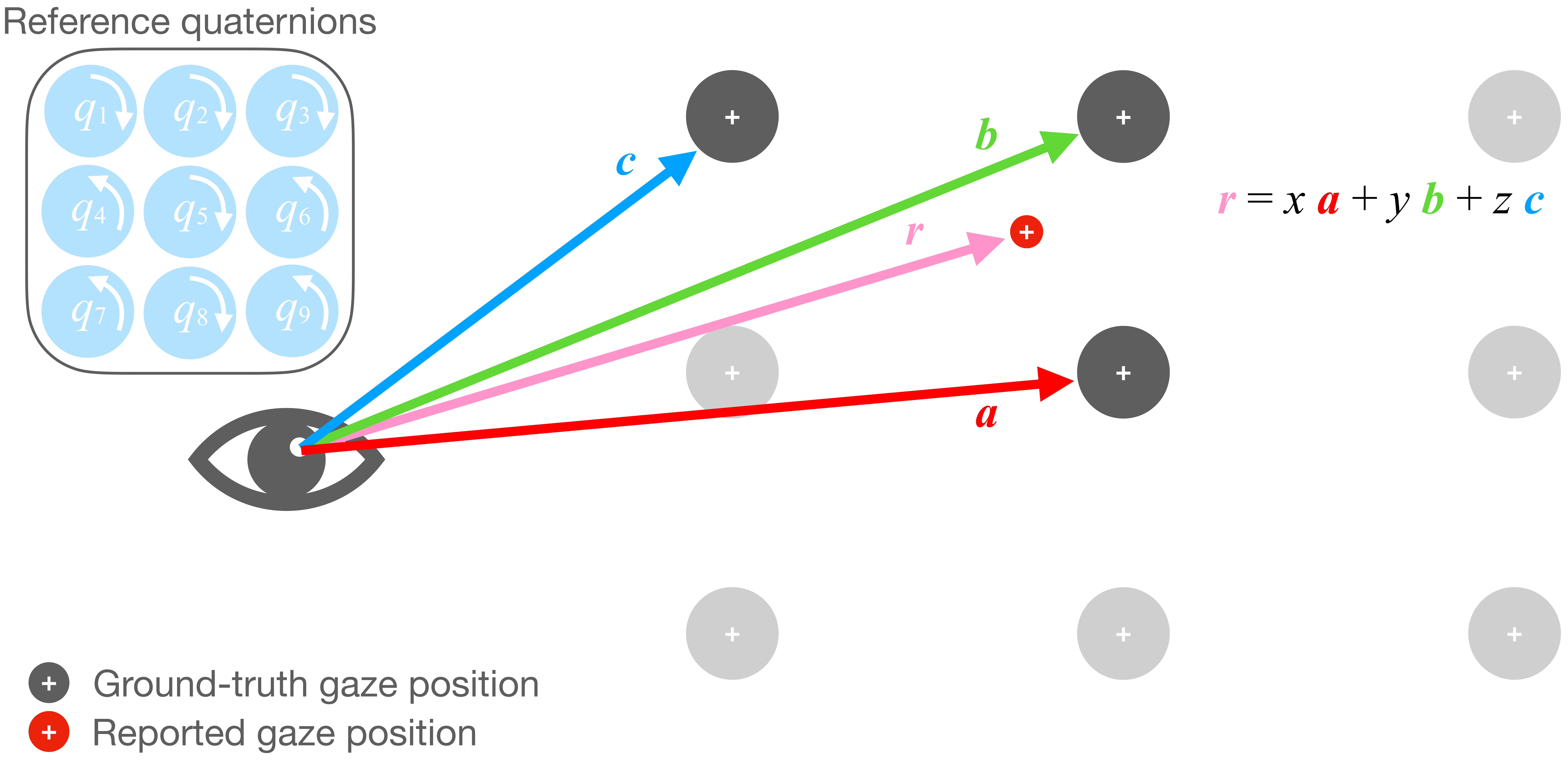


+ Ground-truth gaze position
+ Reported gaze position


Reference quaternions
q_1 q_2 q_3
q_4 q_5 q_6
q_7 q_8 q_9
r
Ground-truth gaze position
Reported gaze position

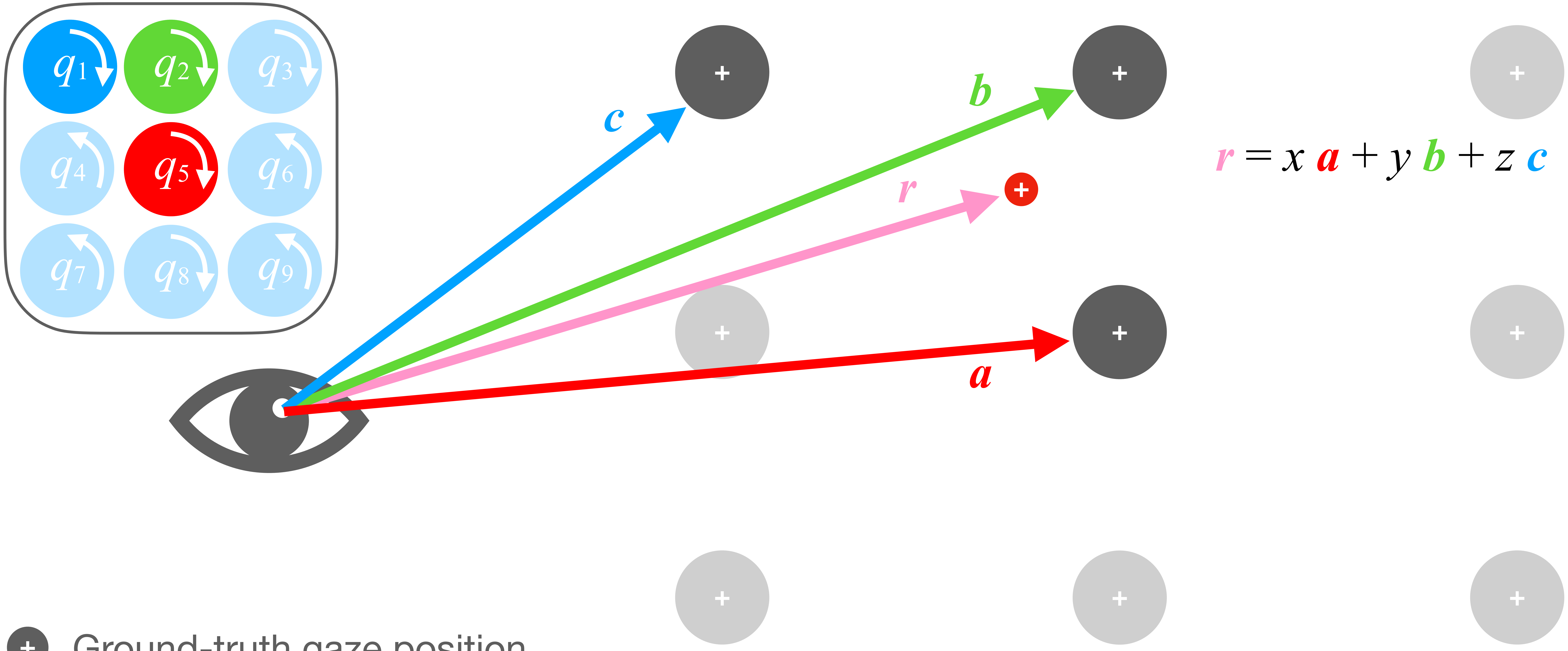
Proposed Uncertainty Mitigation Algorithm: Interpolation




Reference quaternions
q_1 q_2 q_3
q_4 q_5 q_6
q_7 q_8 q_9
c
b
r
a
$r = x\,a + y\,b + z\,c$
Ground-truth gaze position
Reported gaze position

Proposed Uncertainty Mitigation Algorithm: Interpolation

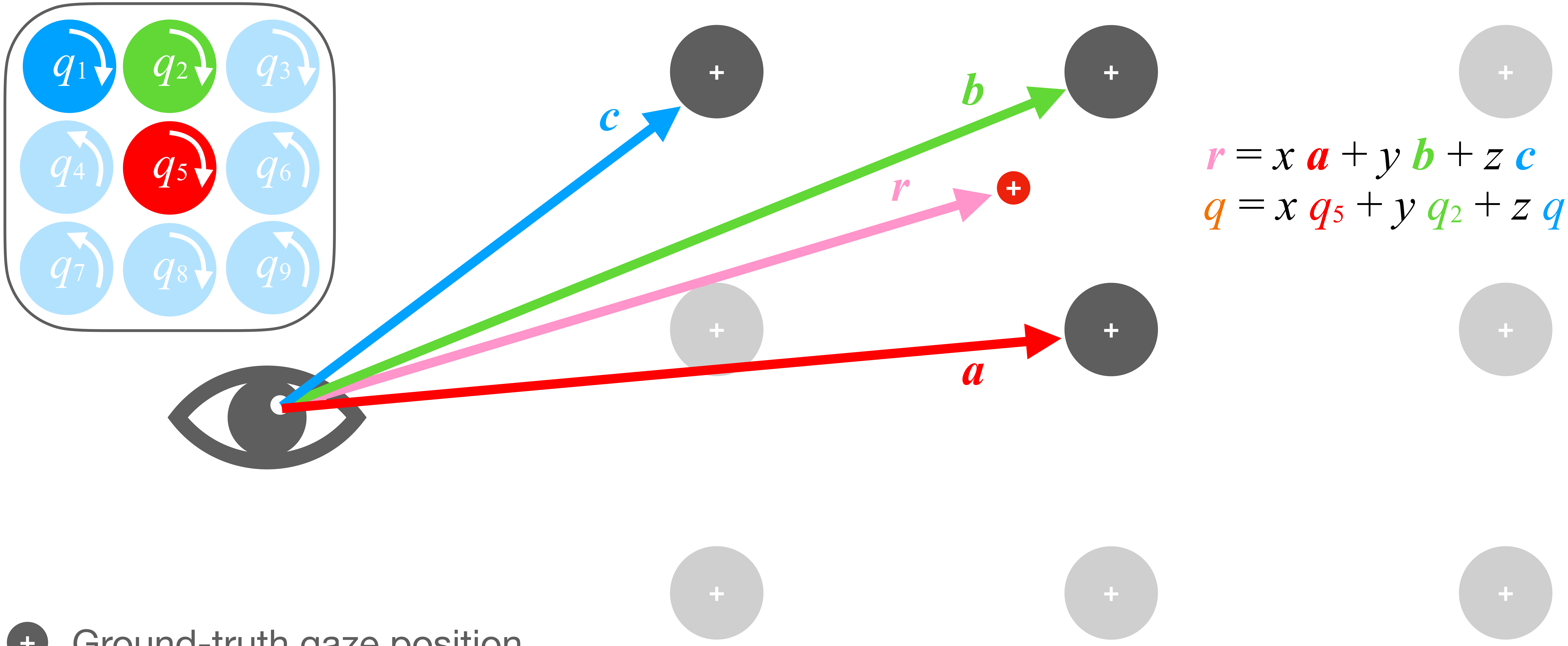
Reference quaternions



$$r = x\,a + y\,b + z\,c$$

- Ground-truth gaze position
- Reported gaze position

Reference quaternions



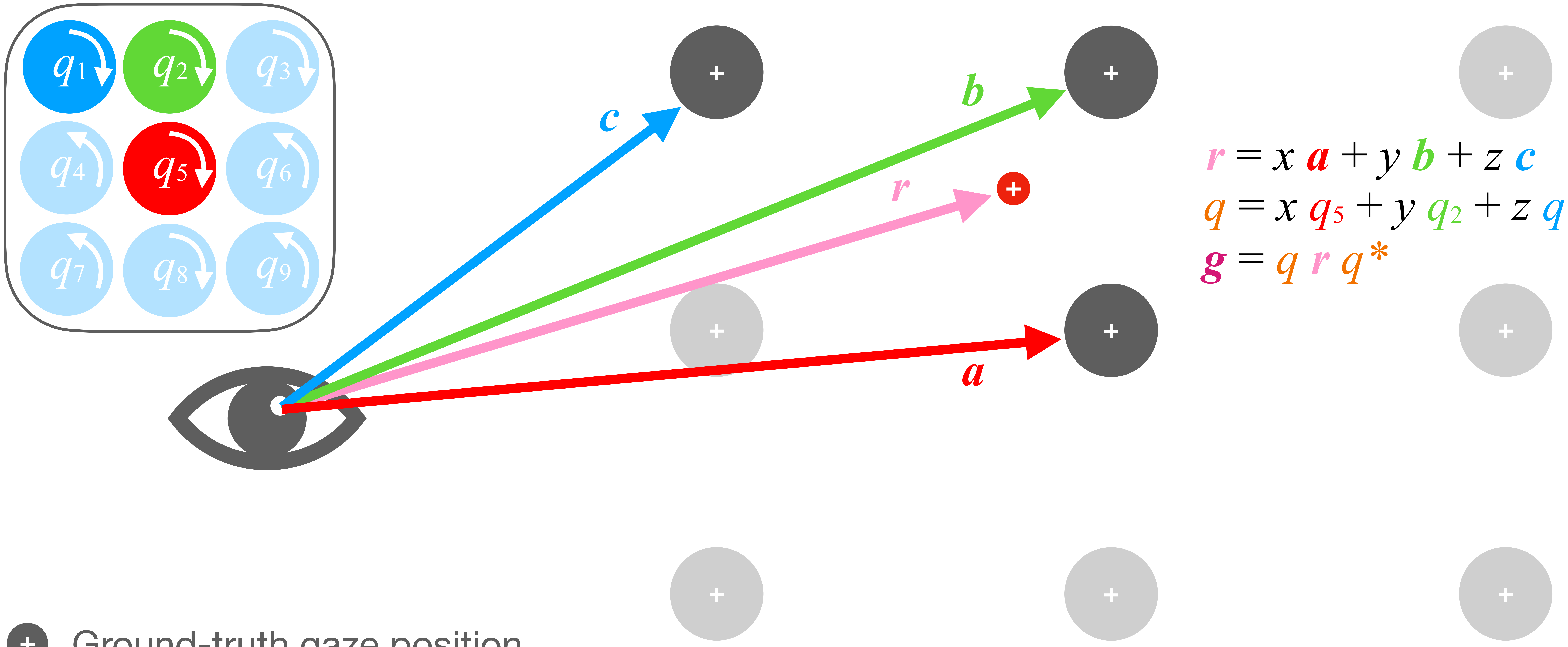
$$r = x\,a + y\,b + z\,c$$
$$q = x\,q_5 + y\,q_2 + z\,q_1$$

Ground-truth gaze position

Reported gaze position

Proposed Uncertainty Mitigation Algorithm: Interpolation

Reference quaternions



$$\mathbf{r} = x\,\mathbf{a} + y\,\mathbf{b} + z\,\mathbf{c}$$
$$q = x\,q_5 + y\,q_2 + z\,q_1$$
$$\mathbf{g} = q\,\mathbf{r}\,q^*$$

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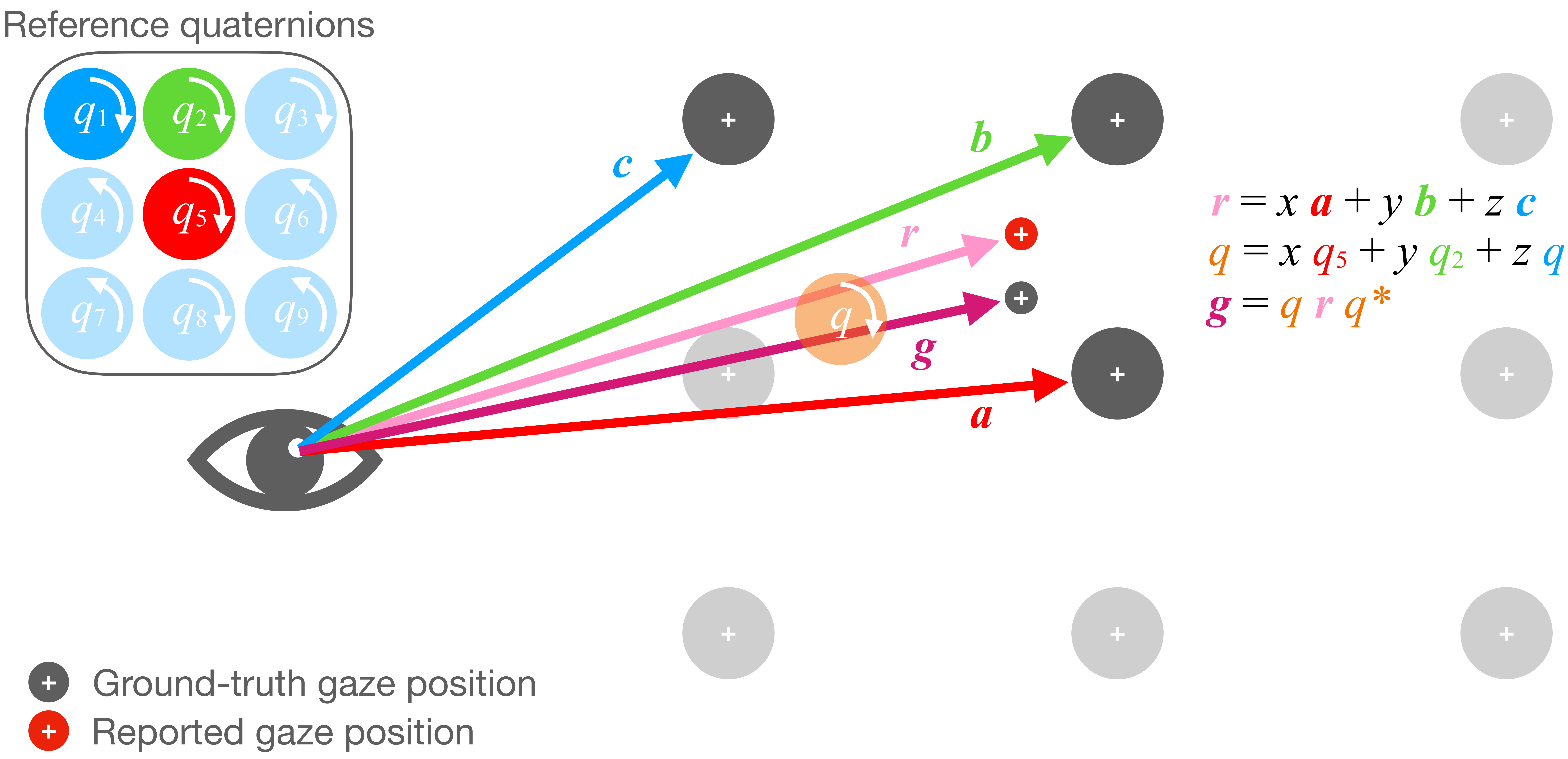

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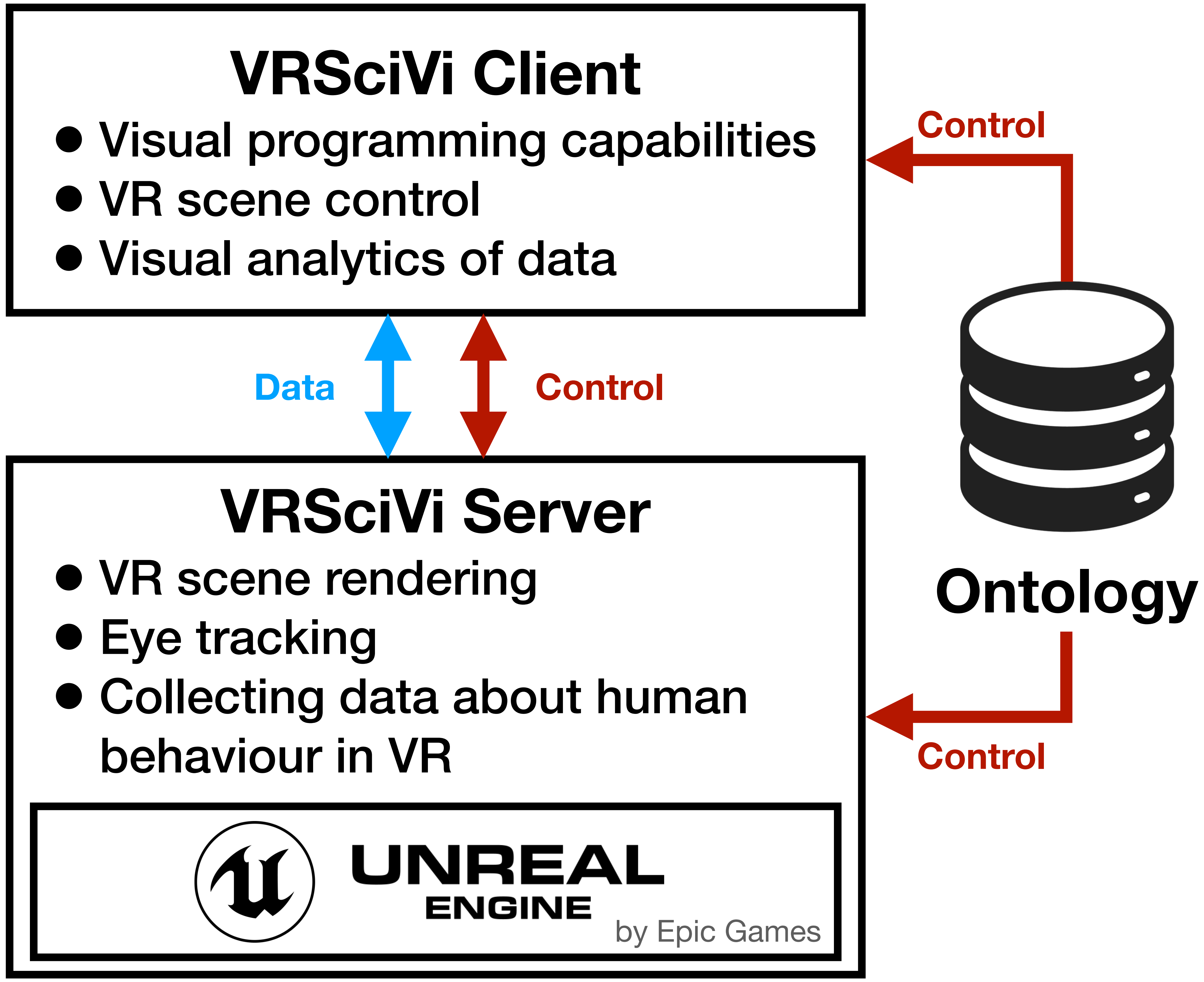
Implementation of the Proposed Algorithm in VRSciVi

VRSciVi – ontology-driven workbench for conducting experiments in VR

(open source project, https://scivi.tools/vrscivi)



Implementation of the Proposed Algorithm in VRSciVi

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VRSciVi Client

- Visual programming capabilities
- VR scene control
- Visual analytics of data

Data | Control

VRSciVi Server

- VR scene rendering
- Eye tracking
- Collecting data about human behaviour in VR

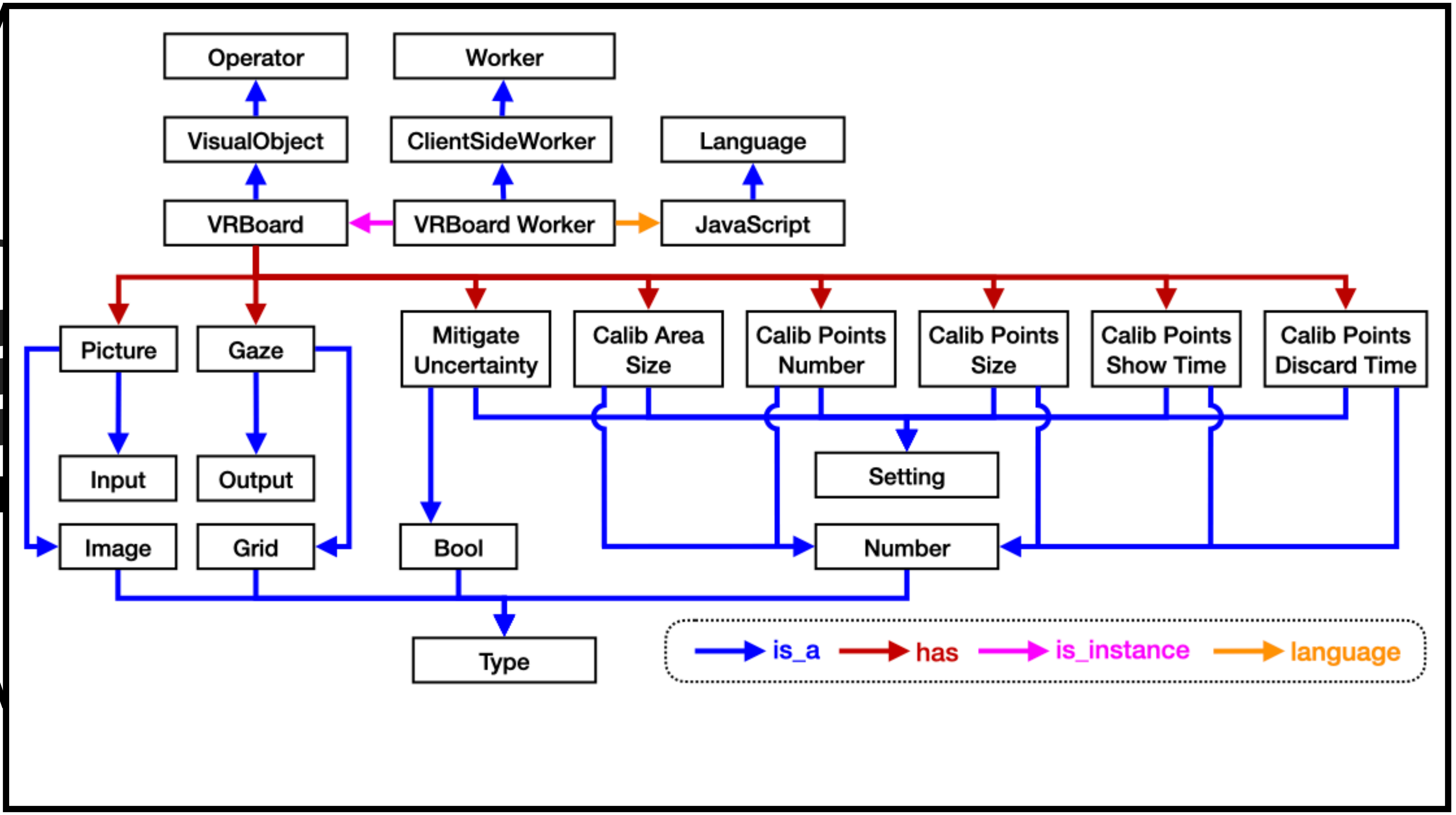
UNREAL ENGINE by Epic Games

Control

Control

Ontol

Ontology of an operator that controls VR scenes



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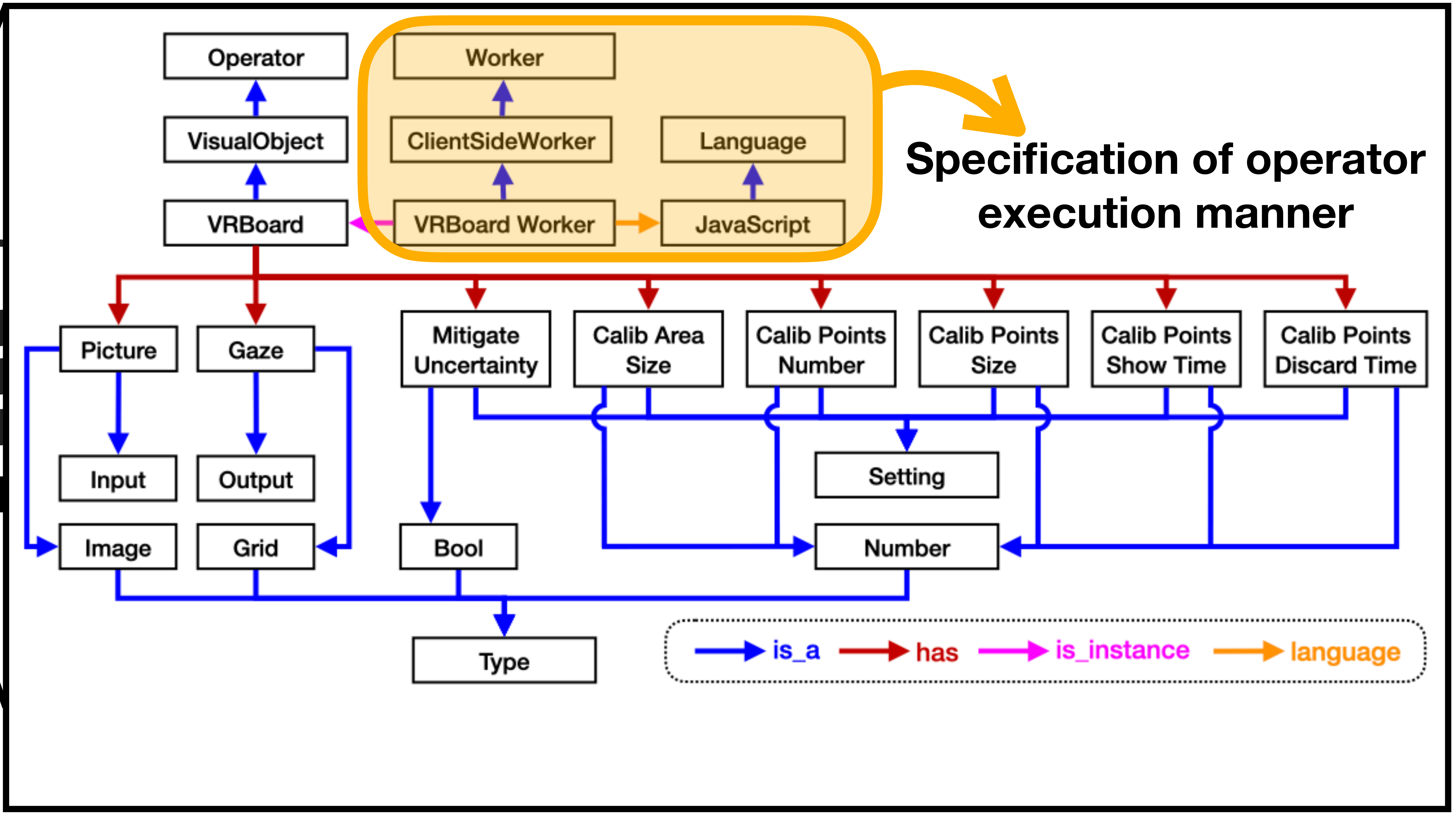

Specification of operator execution manner

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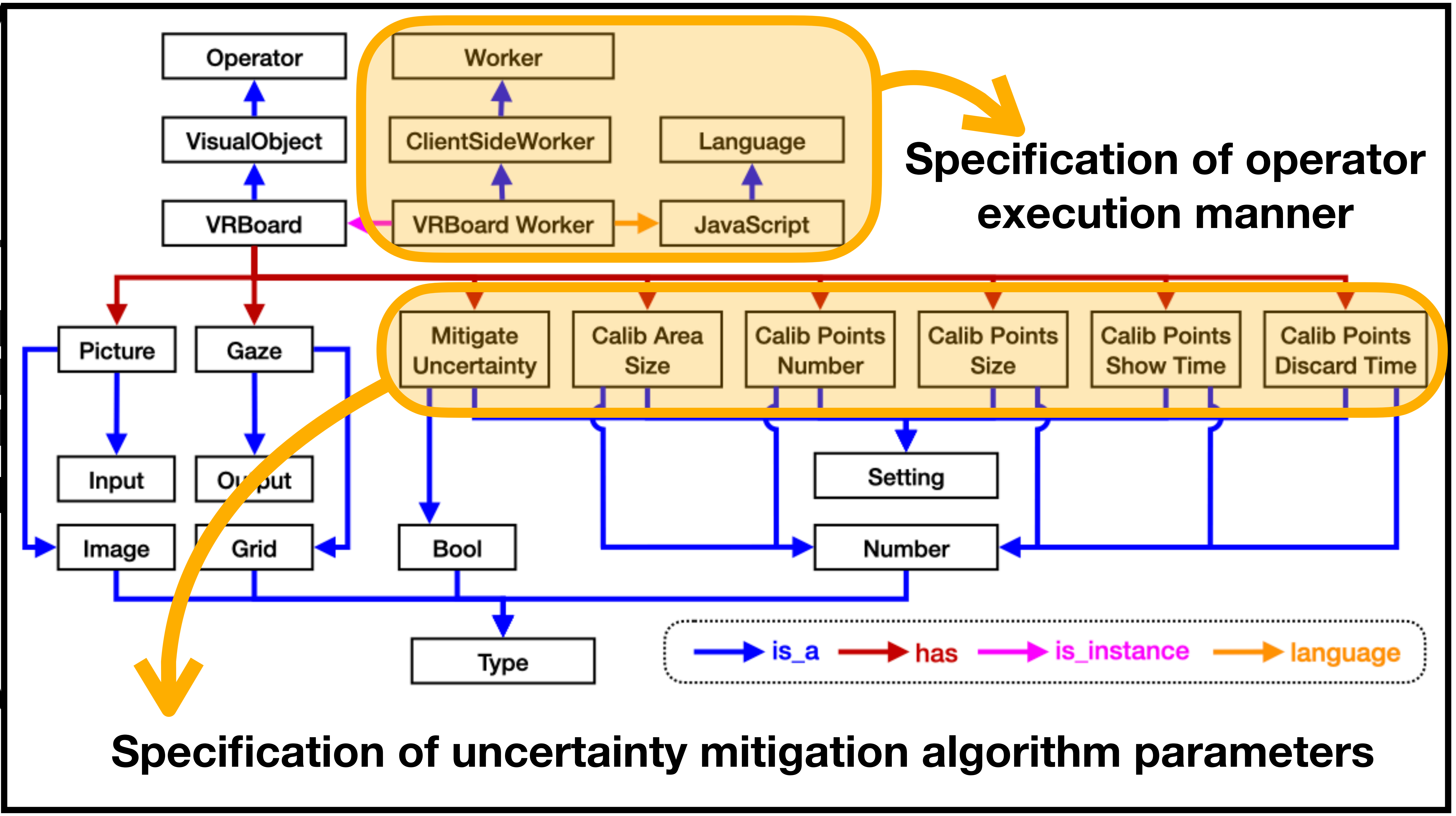

Implementation of the Proposed Algorithm in VRSciVi

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Data | Control

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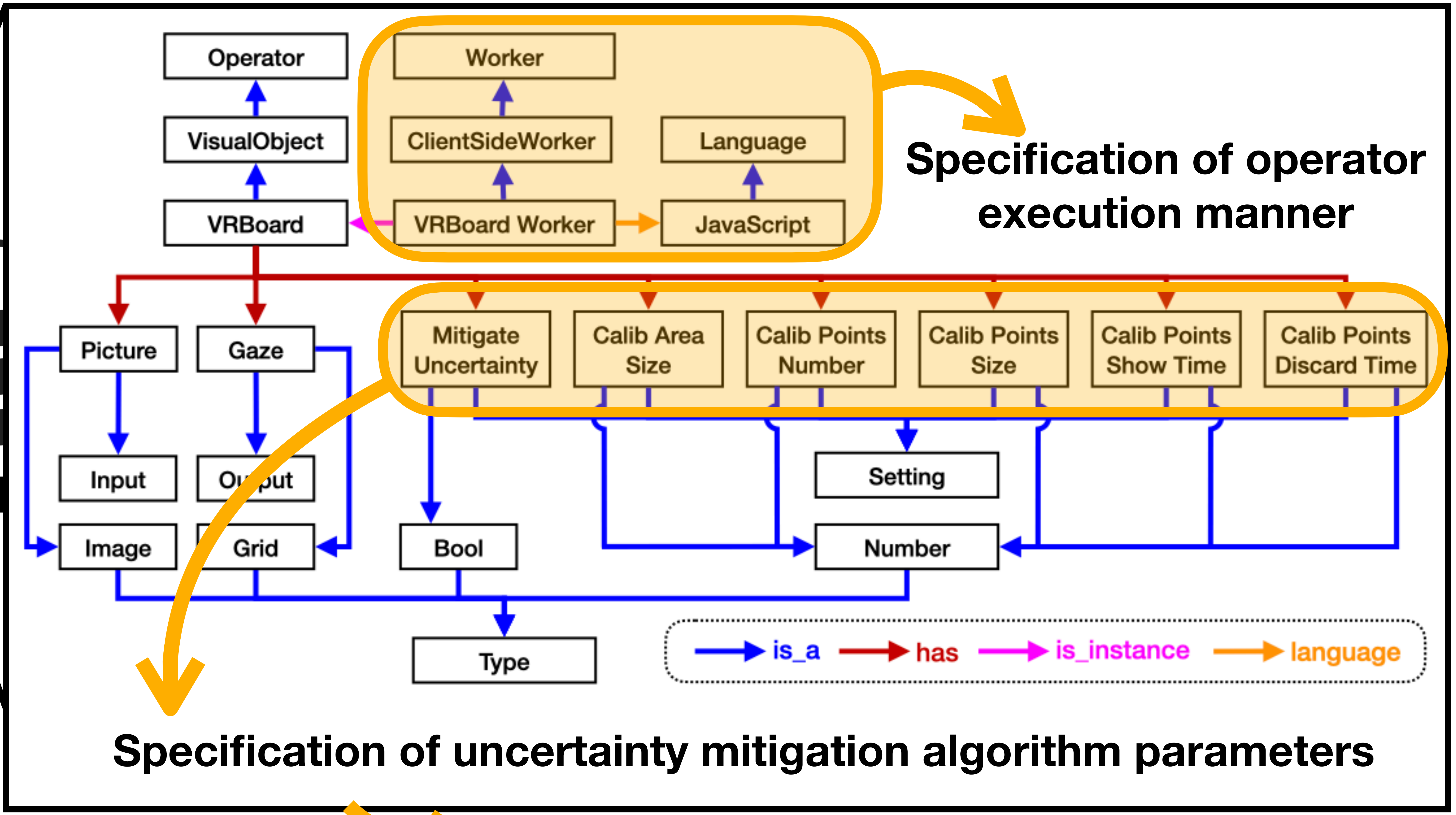
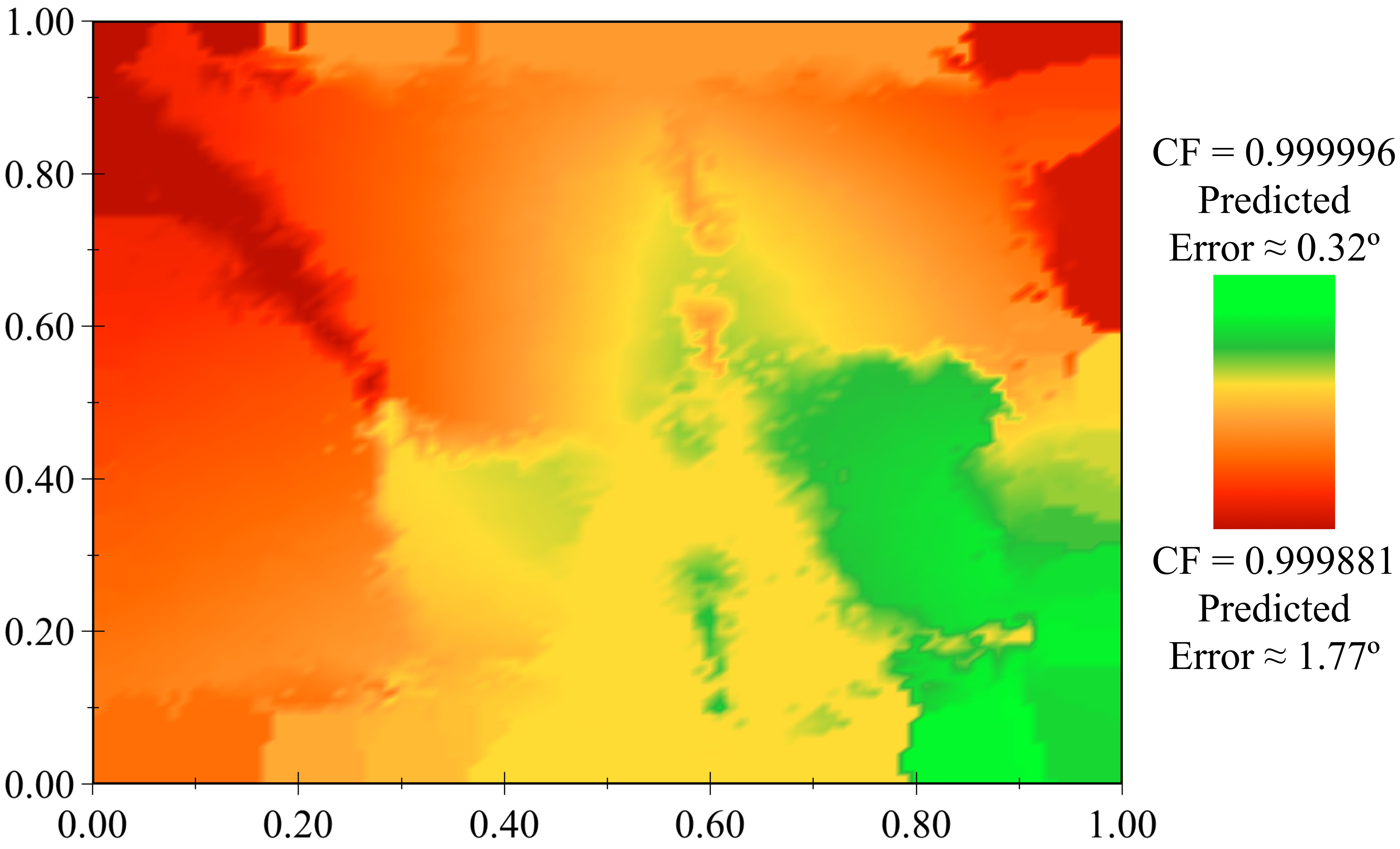
Ontol

Ontology of an operator that controls VR scenes

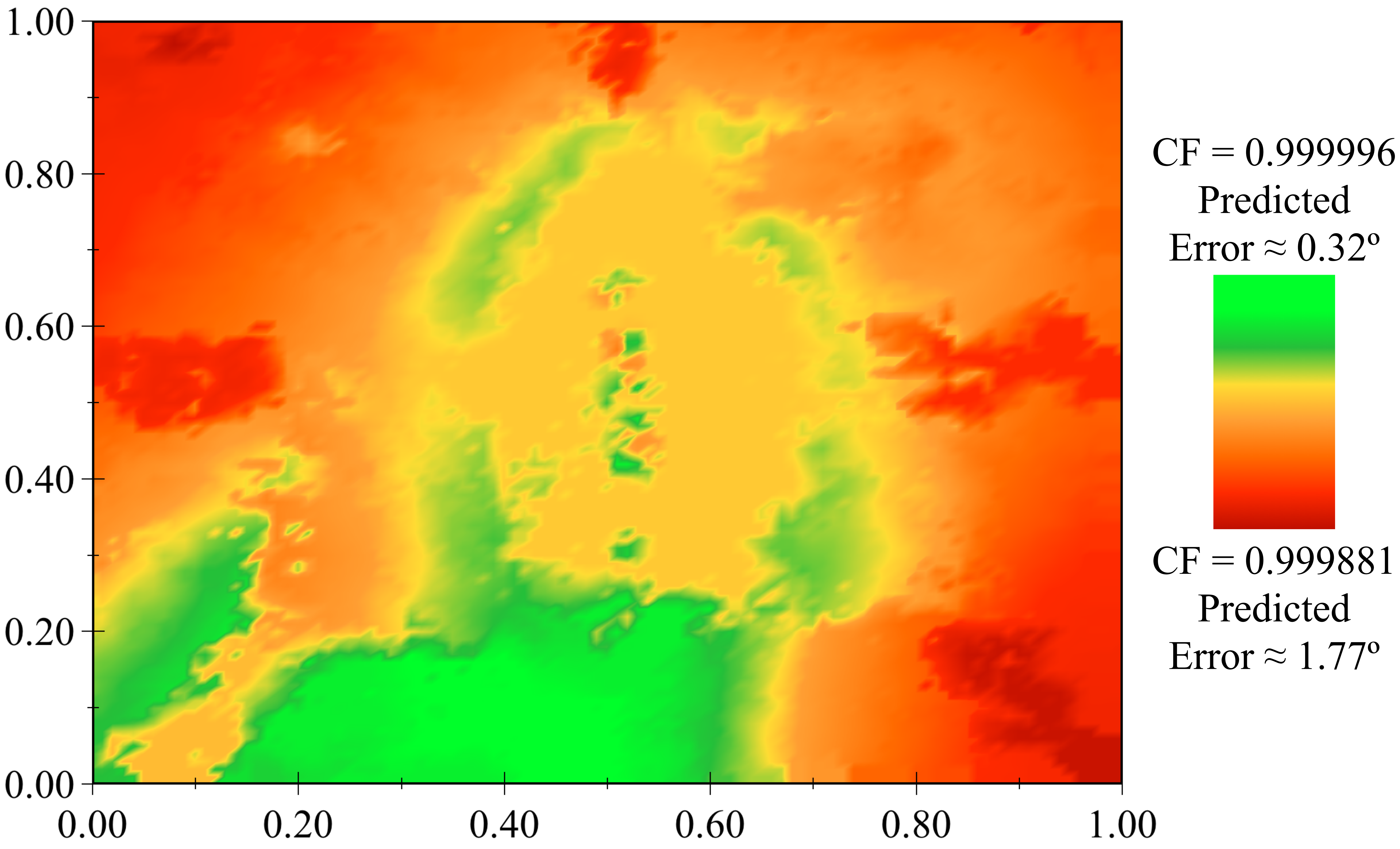


Automatic GUI generation

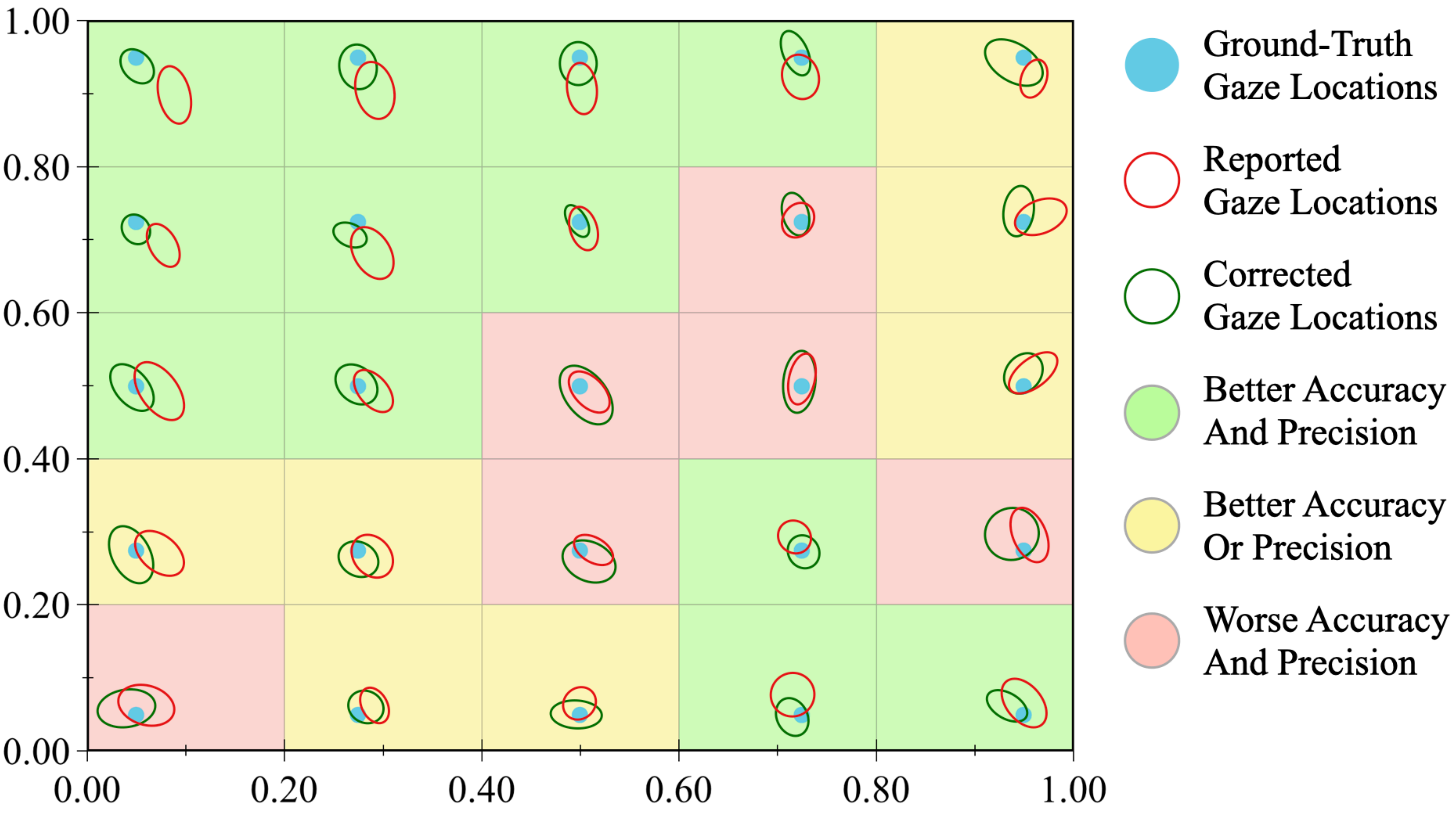
Discussion: Uncertainty Evaluation



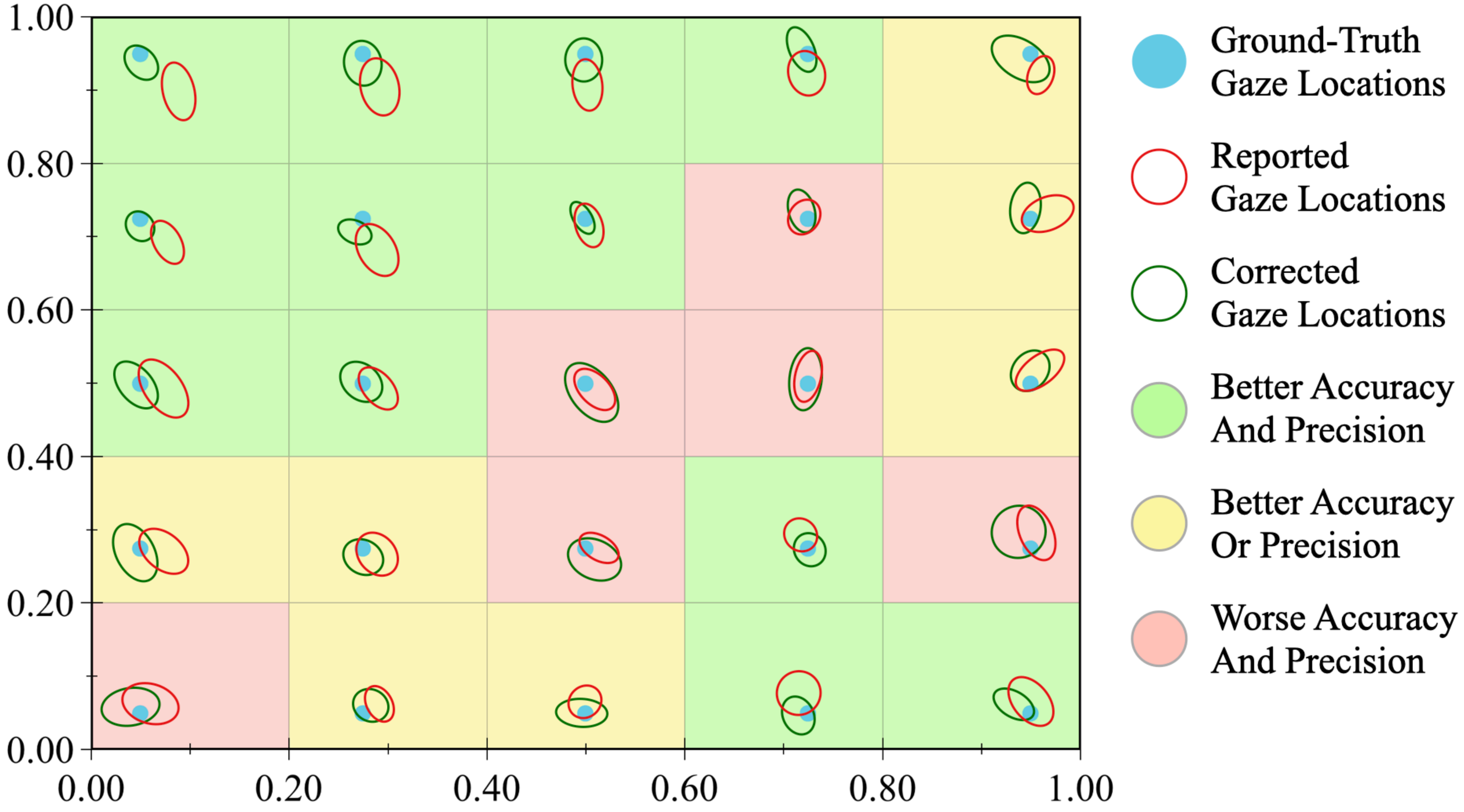
Discussion: Uncertainty Evaluation



Discussion: Uncertainty Mitigation

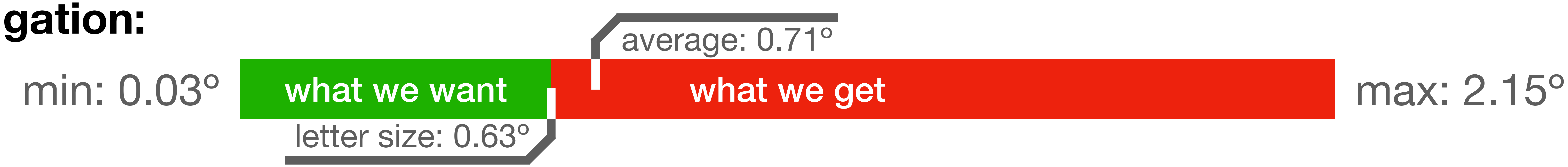


Discussion: Uncertainty Mitigation



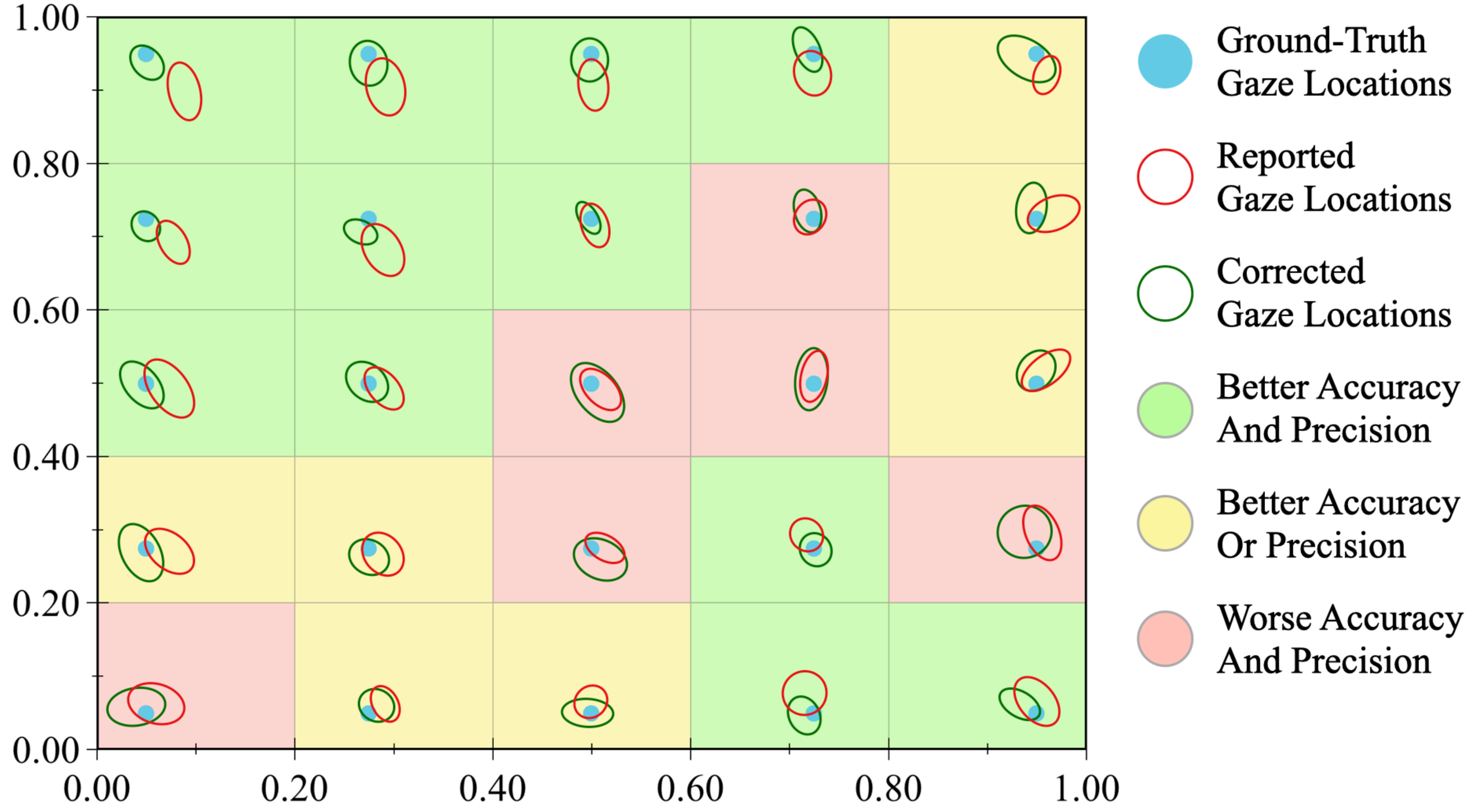
Angular error of gaze positions

Without mitigation:



With mitigation:

Discussion: Uncertainty Mitigation



Angular error of gaze positions

Without mitigation:

average: 0.71°

min: 0.03° what we want what we get max: 2.15°

letter size: 0.63°

With mitigation:

average: 0.53°

min: 0.0° what we want what we get max: 1.59°

letter size: 0.63°

~30% better

Conclusion

Key results:

1. Novel quaternion-based model of the eye gaze tracking uncertainty
2. Novel algorithm to mitigate the eye gaze tracking uncertainty at runtime
   accuracy +25%, precision +32%
3. Ontology-driven high-level software development tools to generate the interface for parametrization of the proposed algorithm

Outstanding issue:

~30% better – still not enough to study reading

Future work:

Involving machine learning for interpolating quaternions

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Thank you for attention!

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