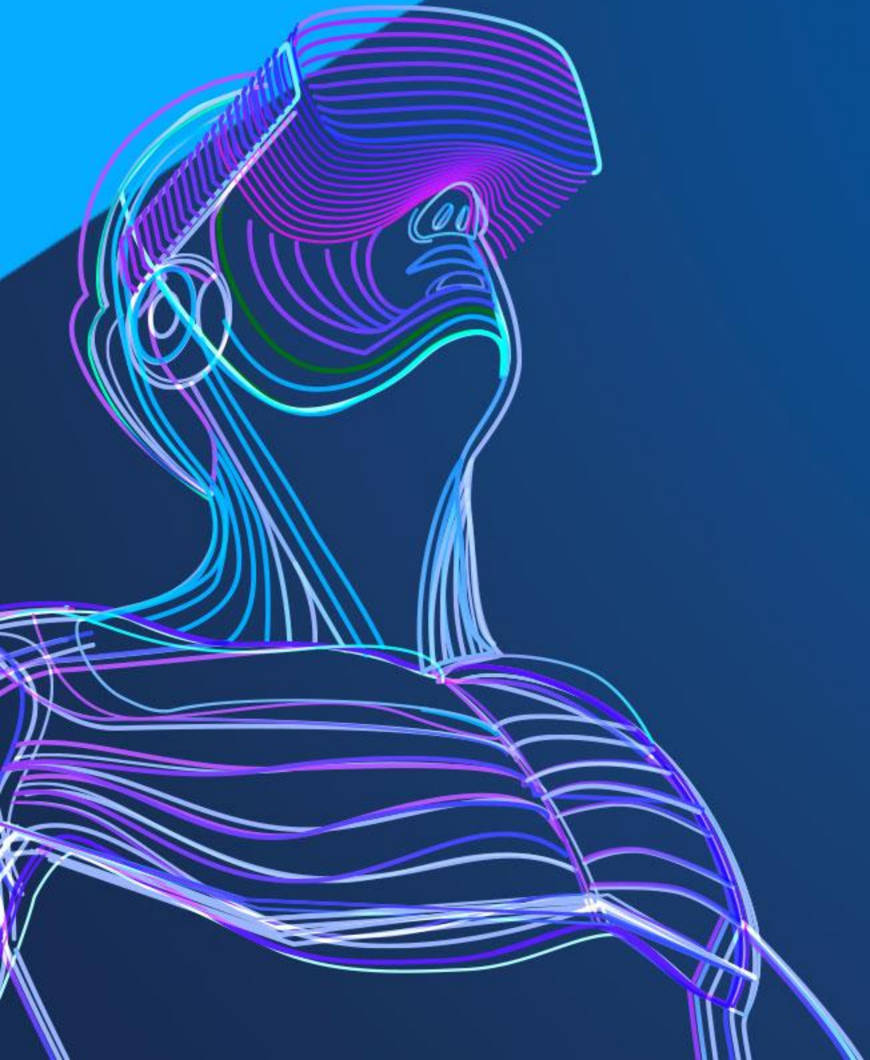
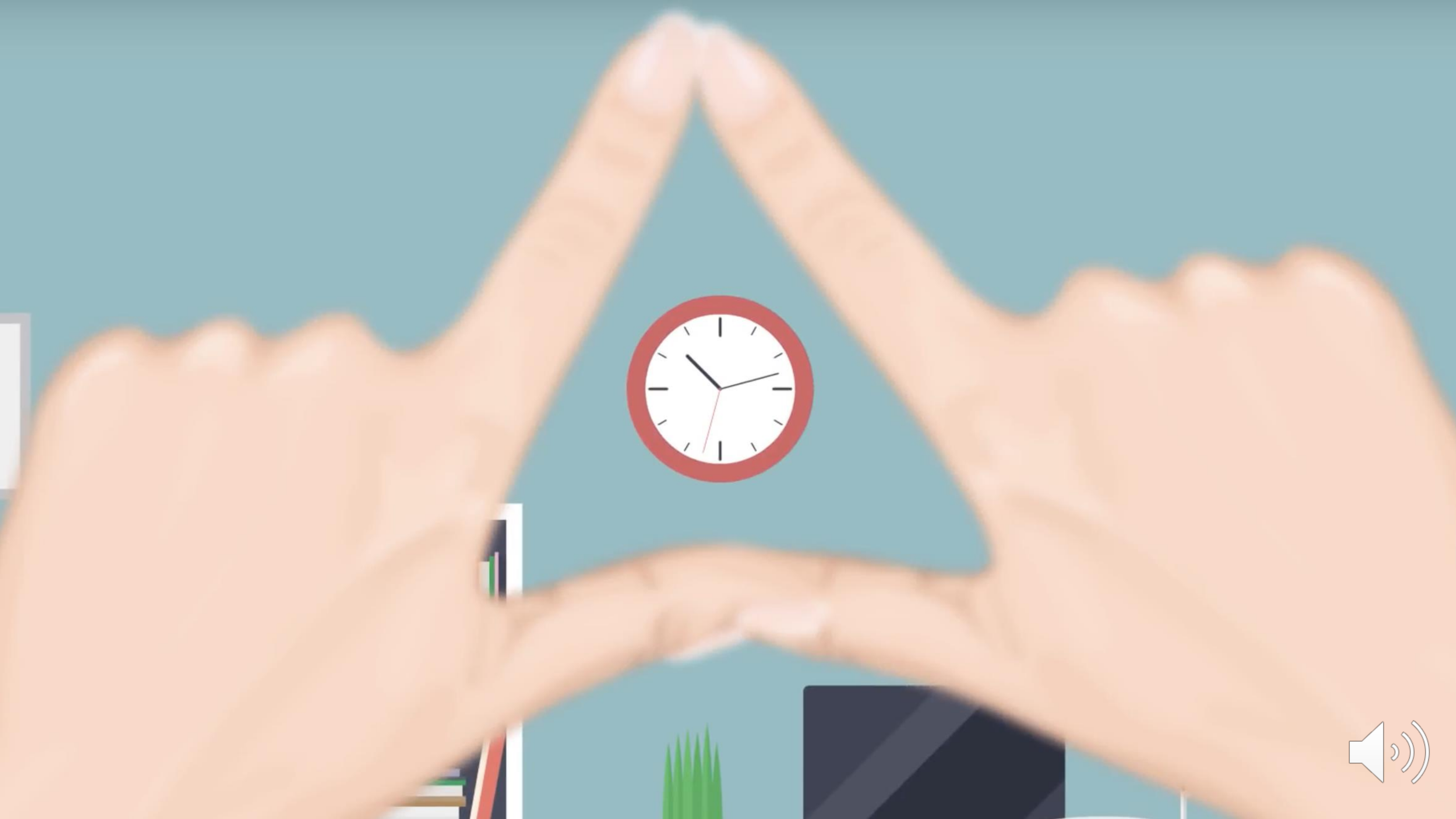
2020 IEEE VR ATLANTA

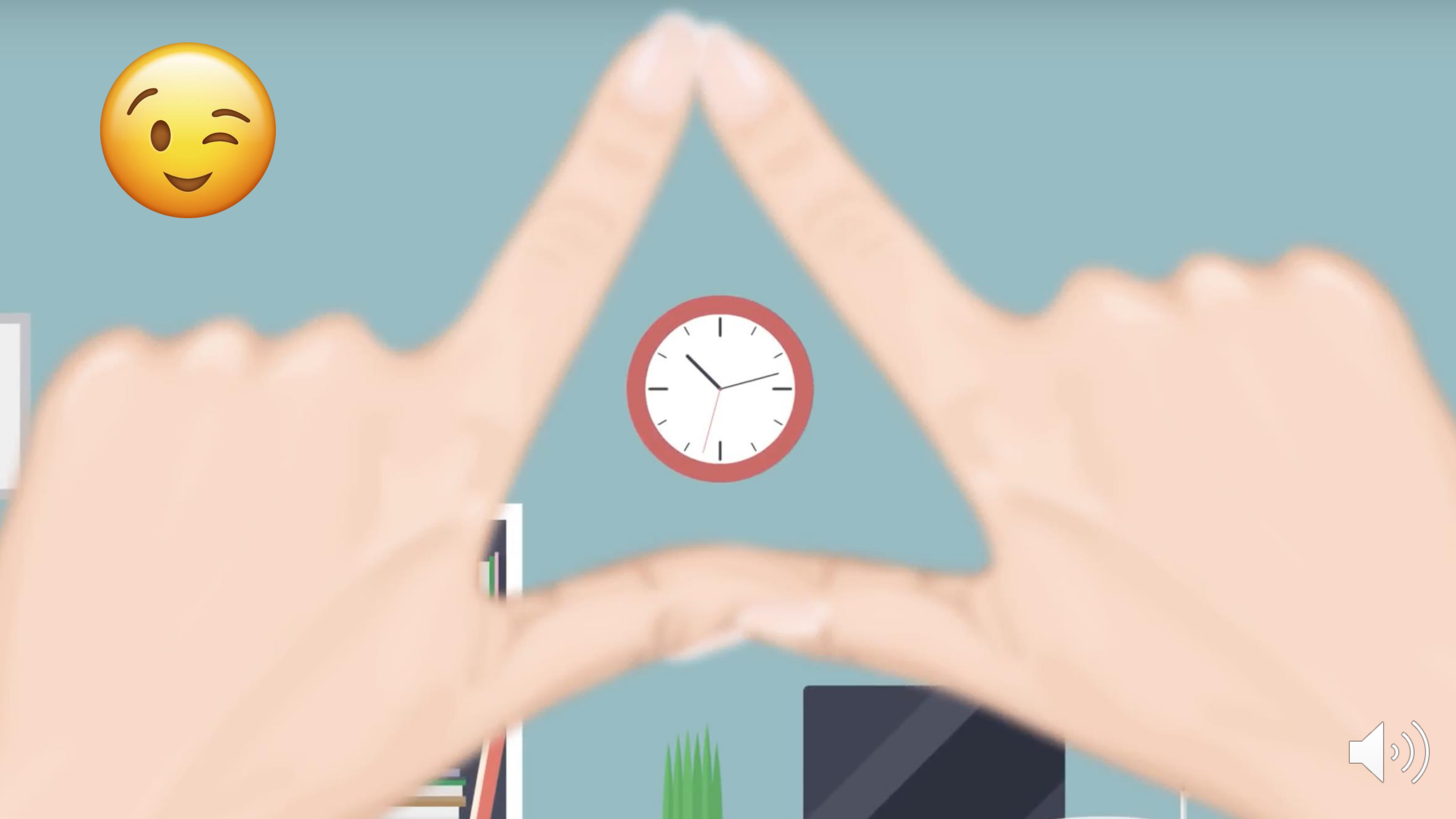


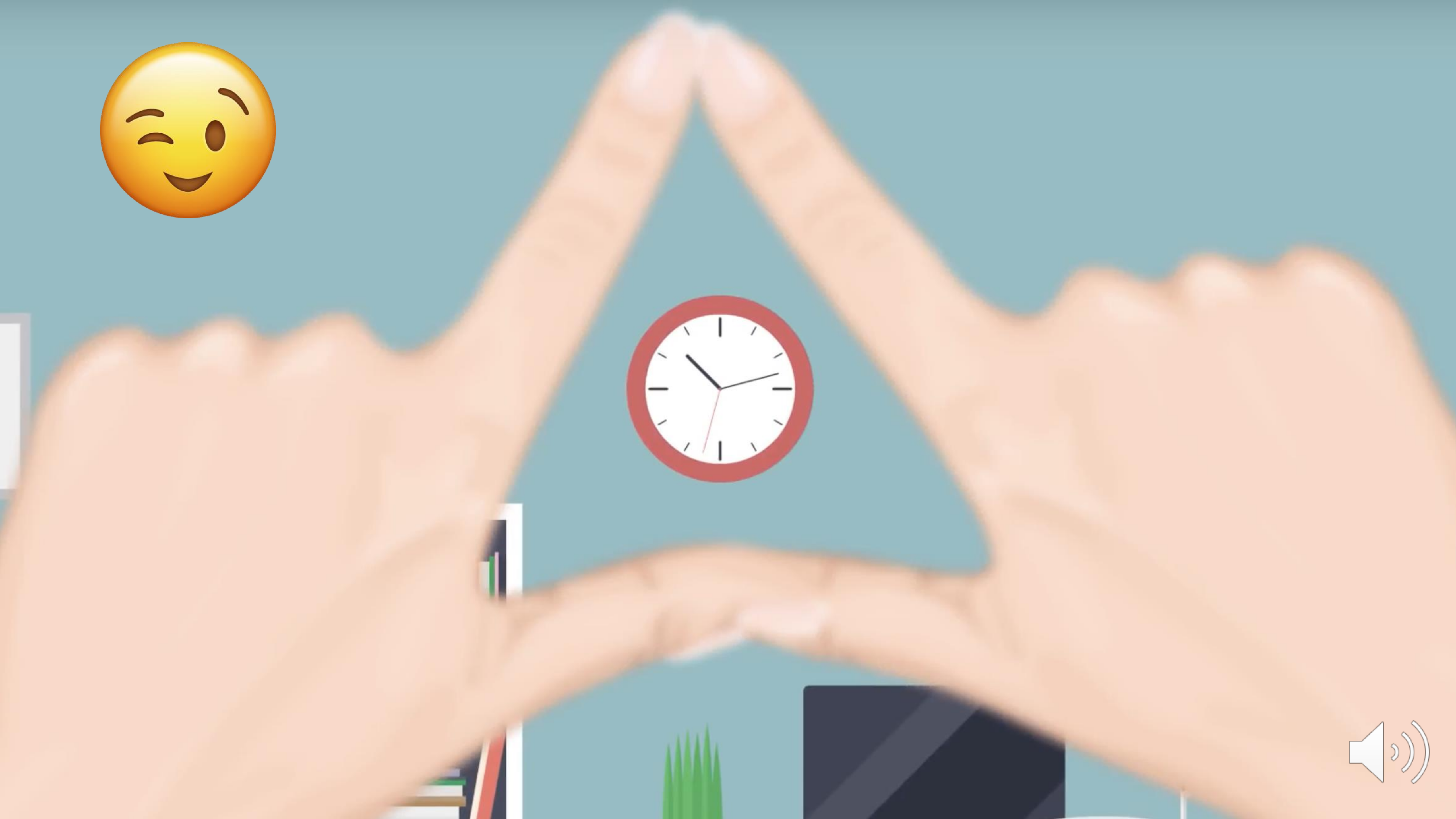
Eye-dominance-guided Foveated Rendering

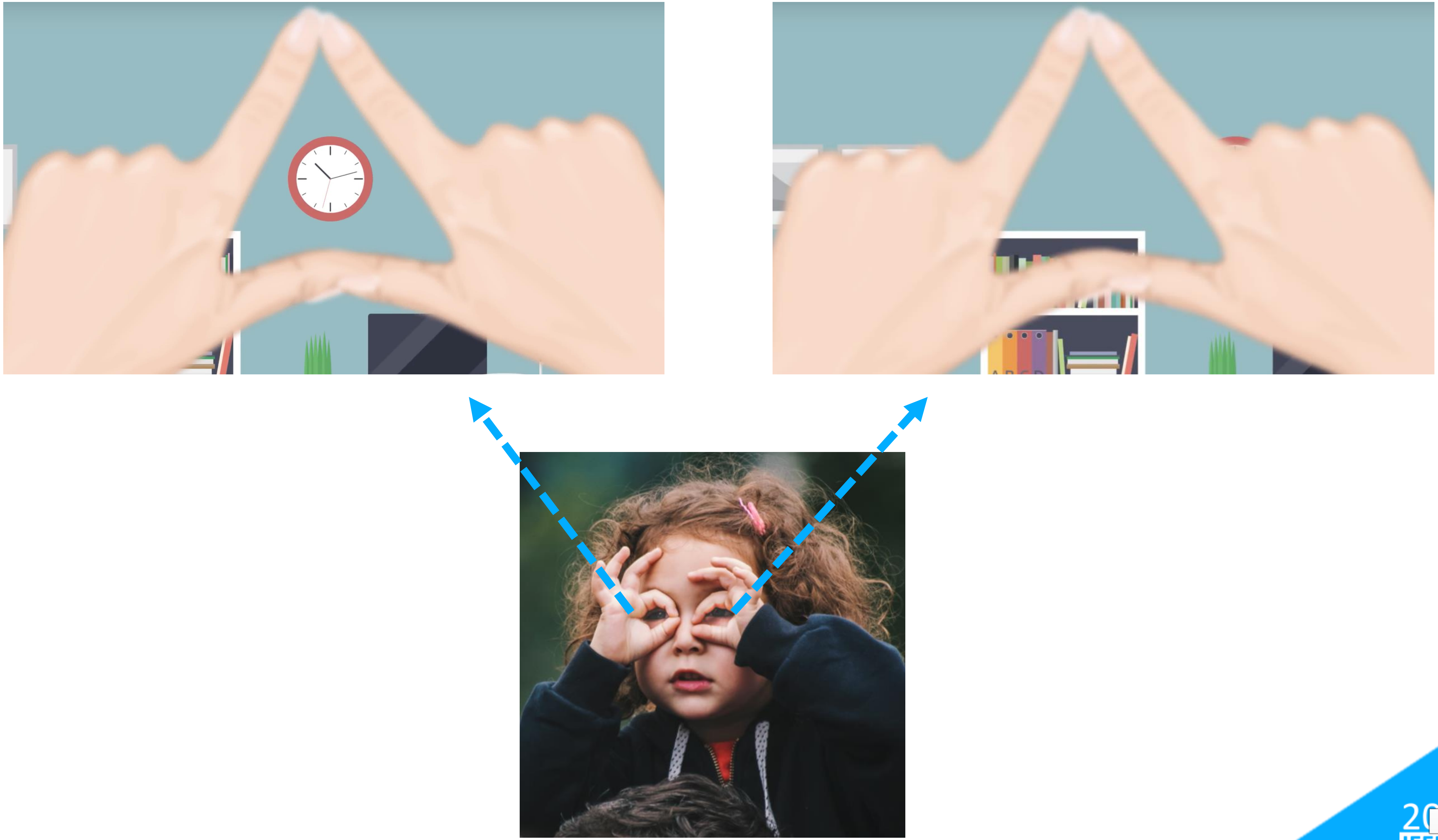
Xiaoxu Meng, Ruofei Du, and Amitabh Varshney

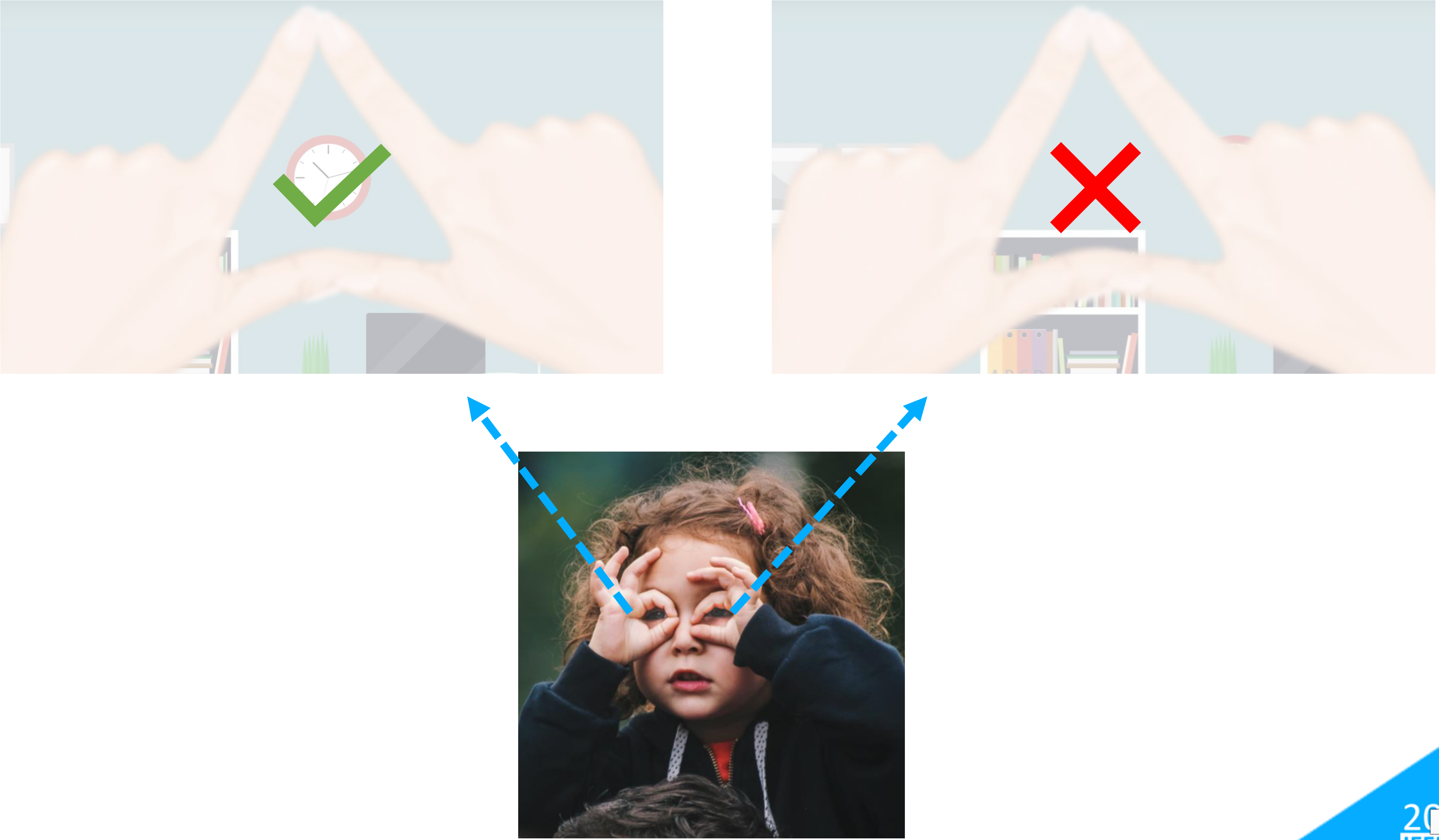
IEEE Transactions on Visualization and Computer Graphics (TVCG)







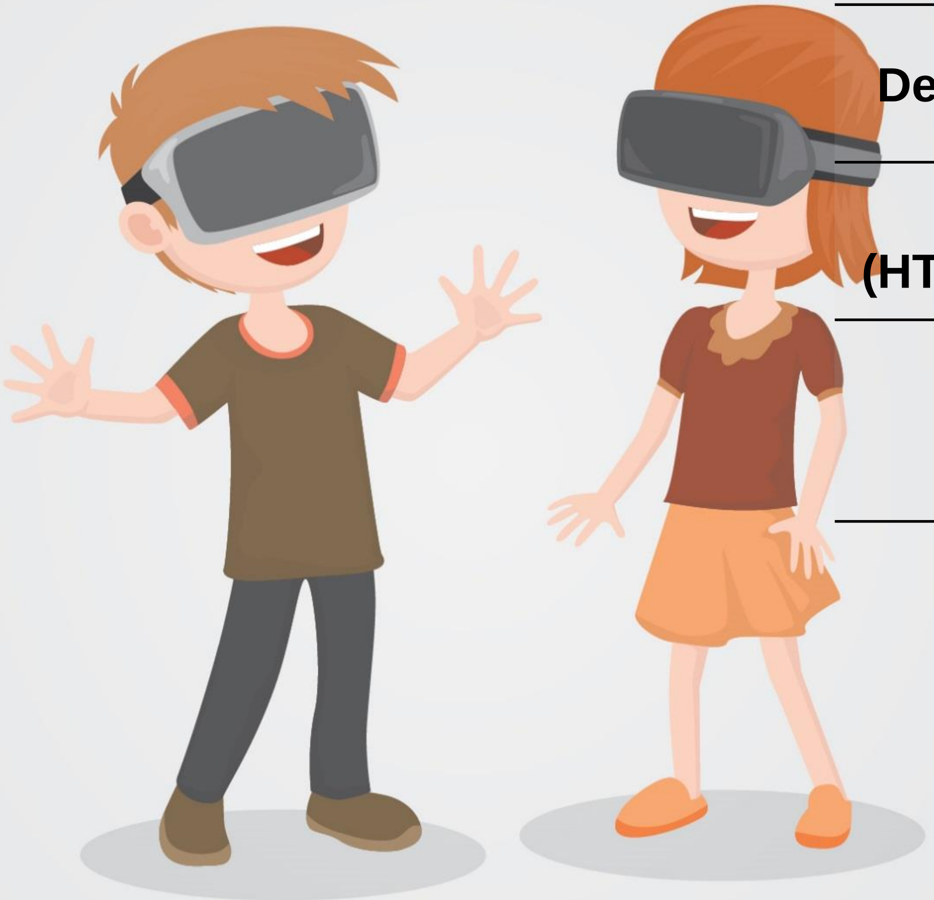




Ocular Dominance: the tendency to prefer scene perception from one eye over the other.

Advantage of the Dominant Eye Over the Non-dominant Eye

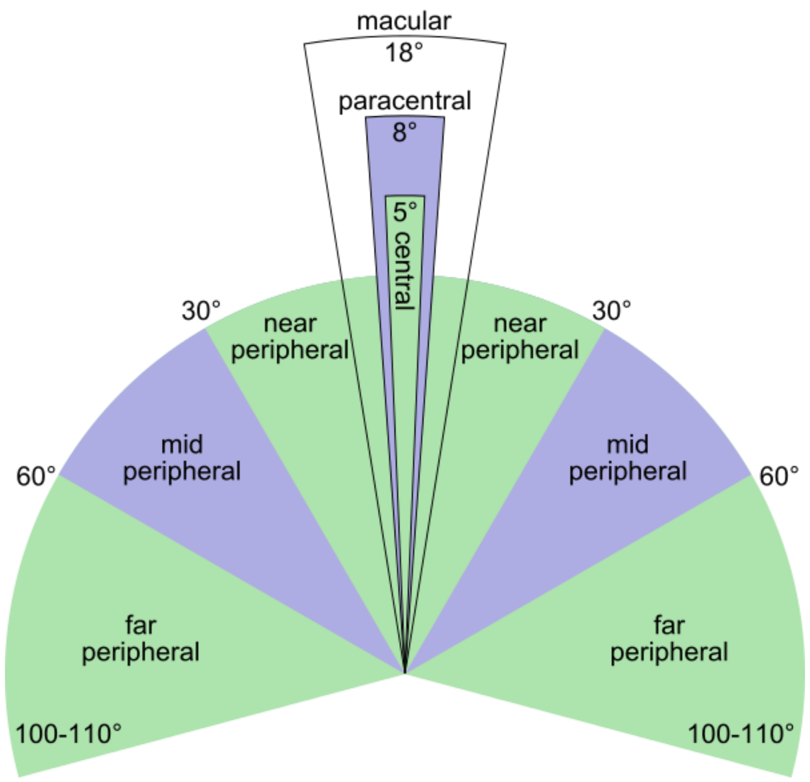
- better color-vision discrimination ability [Koctekin 2013]
- shorter reaction time on visually triggered manual action [Chaumillon 2014]
- better visual acuity, contrast sensitivity [Shneor 2006]



Application	Resolution	Frame rate	MPixels / sec
Desktop game	1920 x 1080 x 1	60	124
2018 VR (HTC Vive PRO)	1440 x 1600 x 2	90	414
2020 VR (Varjo)	1920 x 1080 x 2 + 1440 x 1600 x 2	90	788

Foveated Rendering

- VR requires enormous rendering budget
- Most pixels are outside the fovea



Foveated Rendering

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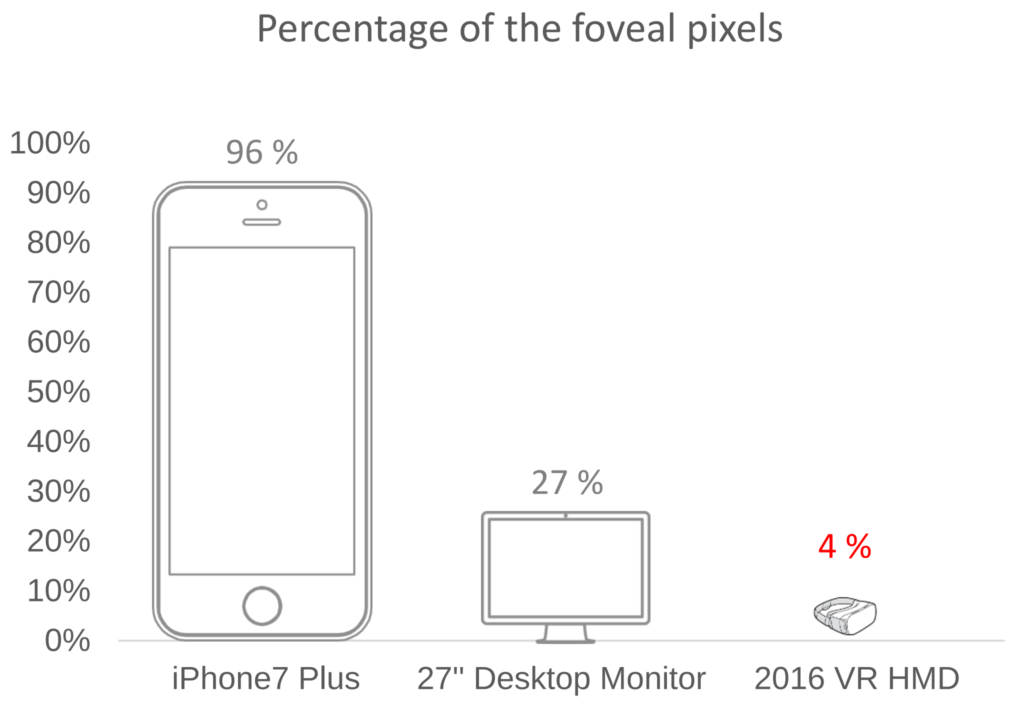
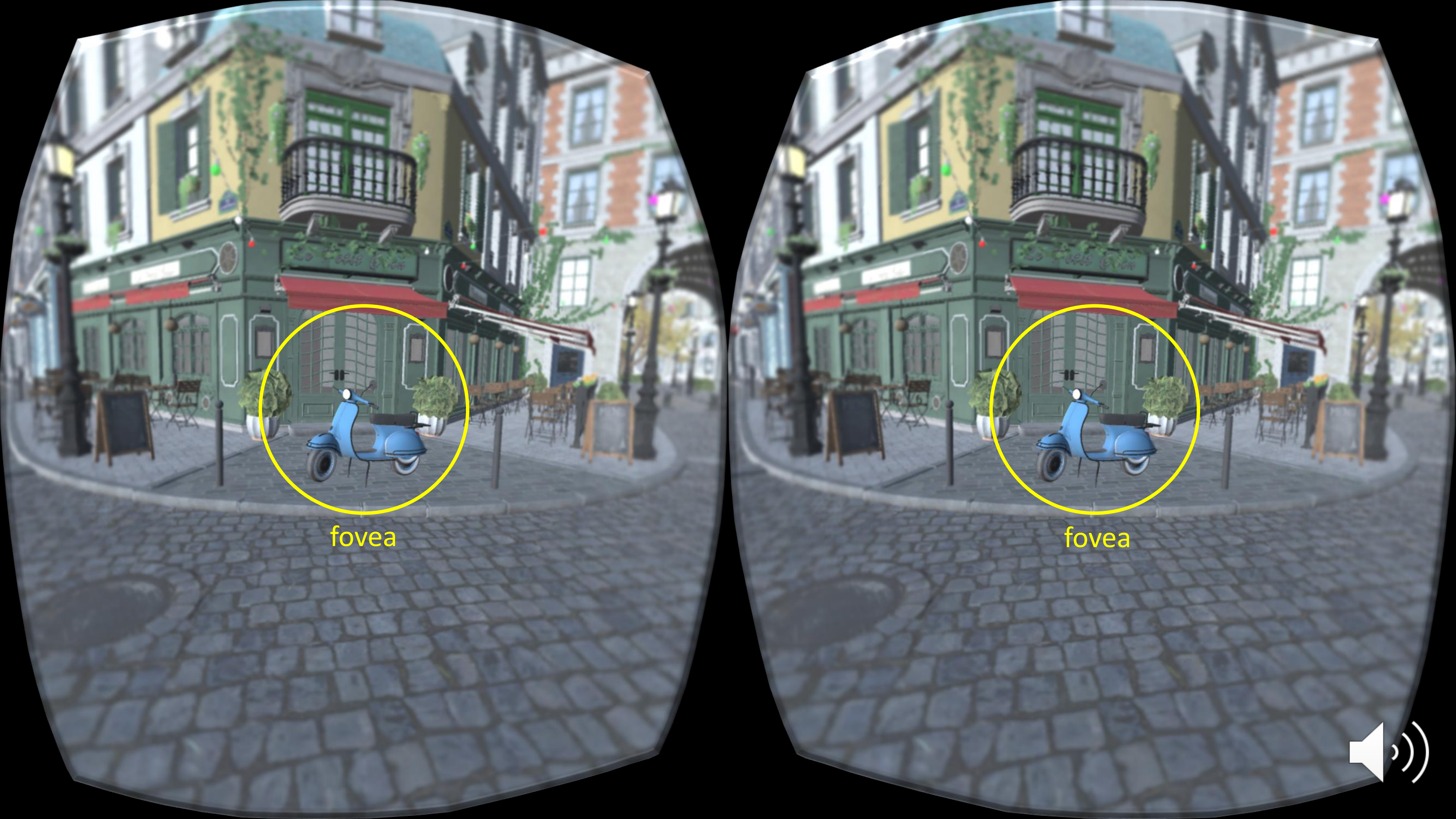
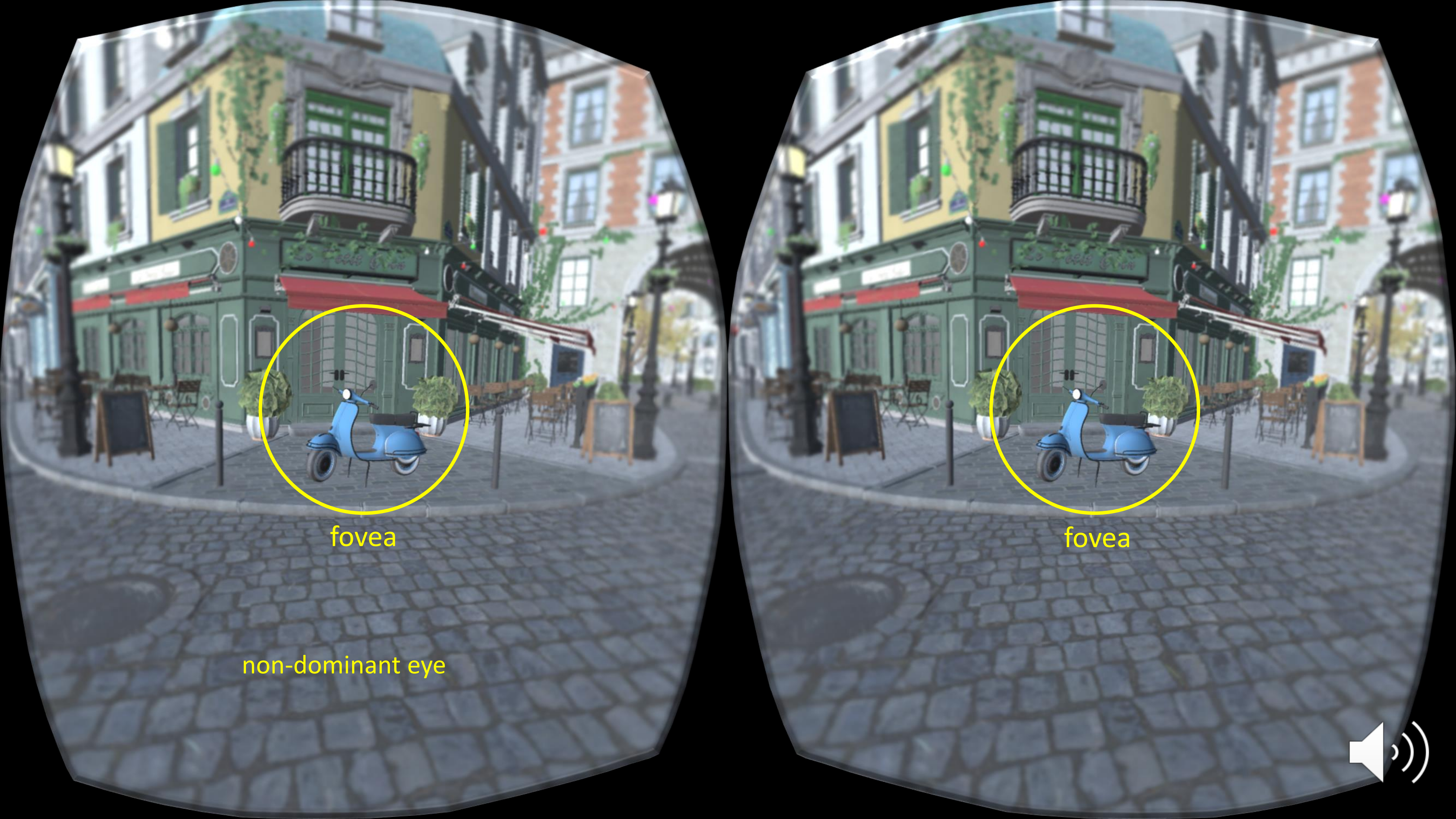


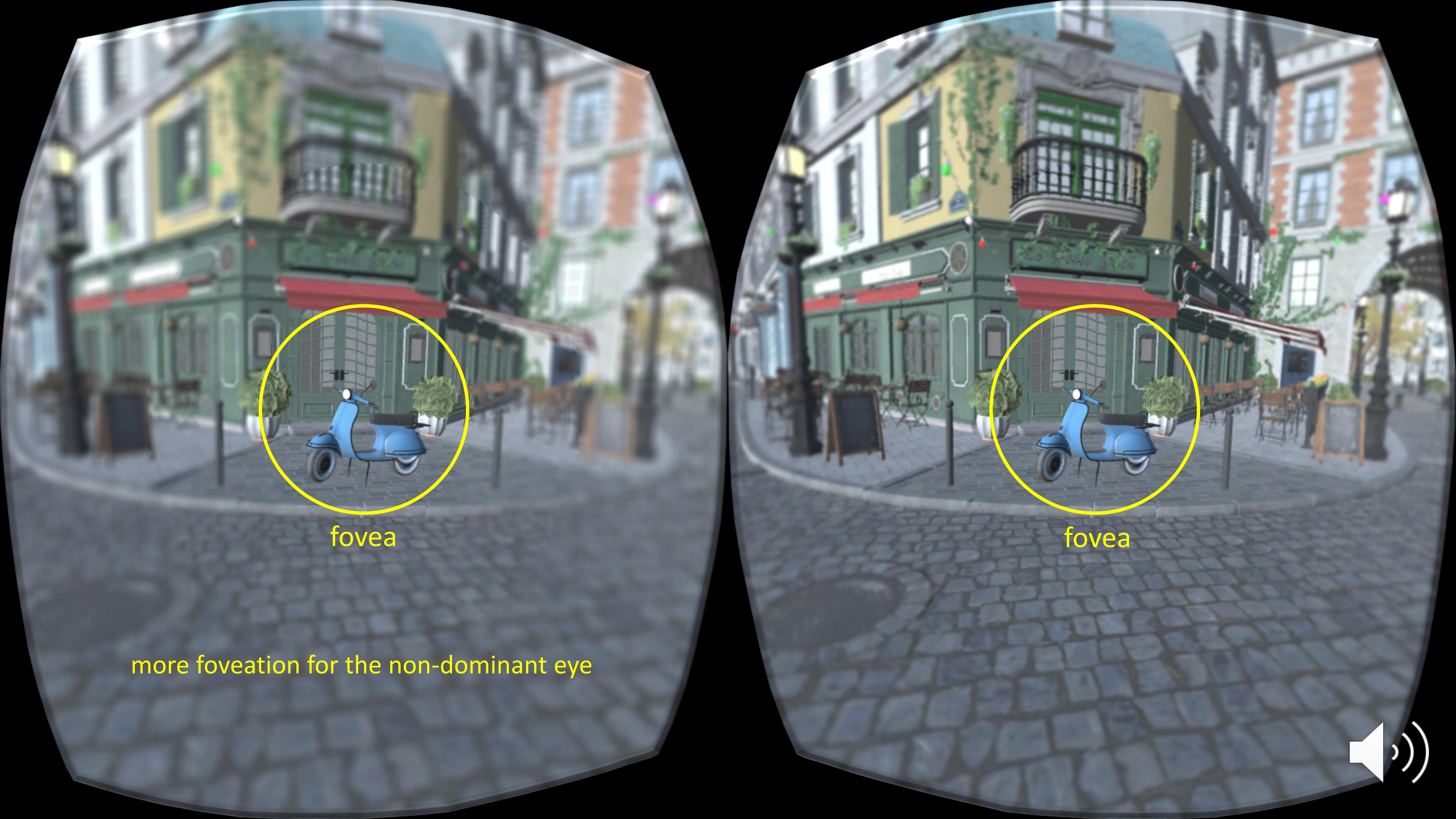
* Data from Siggraph 2017, by Anjul Patney, August 2017


MENU


fovea
fovea

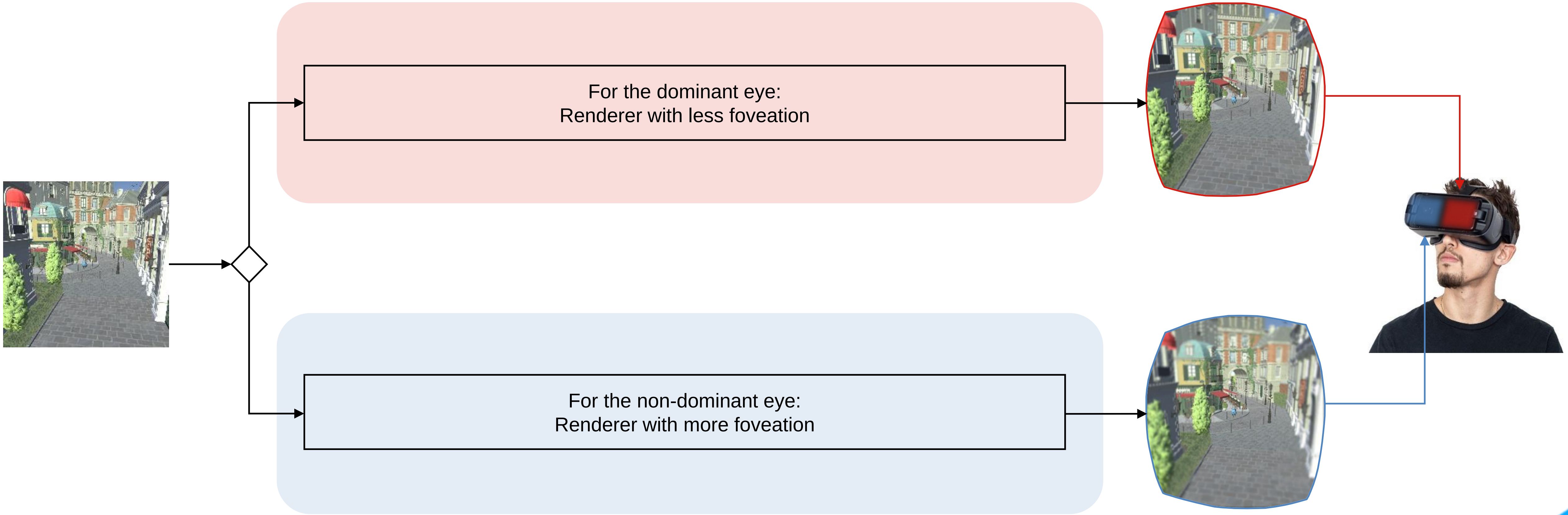
Can we do better?


fovea
fovea
non-dominant eye


fovea
fovea
more foveation for the non-dominant eye

Eye-dominance-guided Foveated Rendering

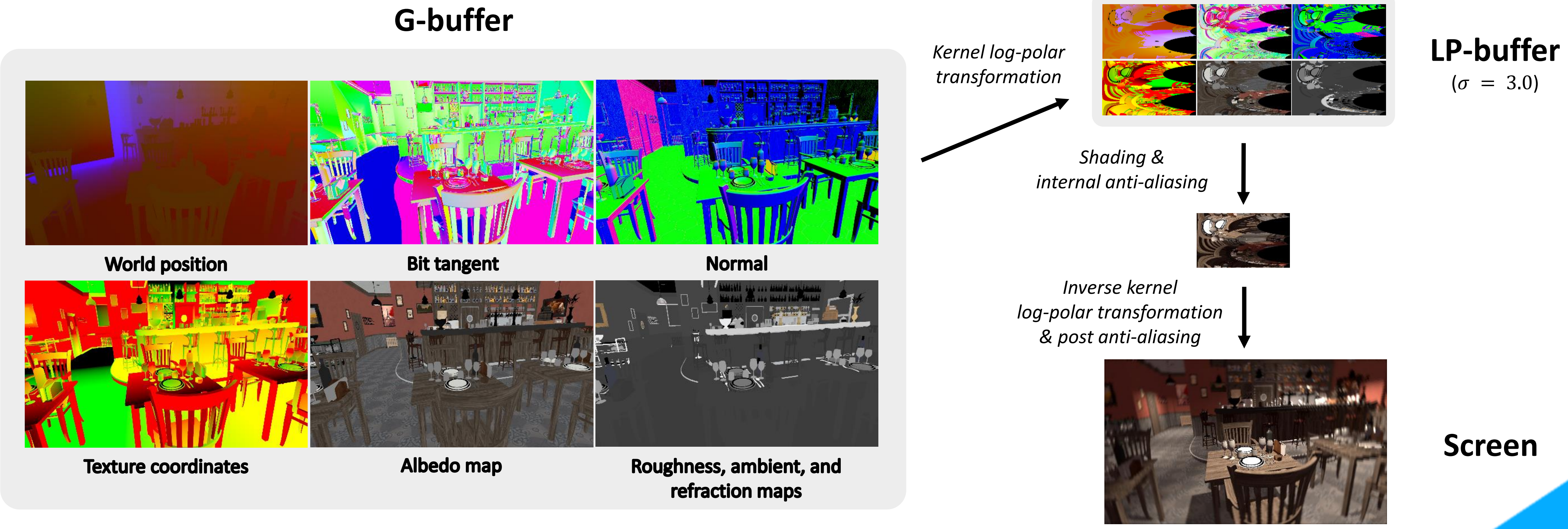
Overview


For the dominant eye:
Renderer with less foveation
For the non-dominant eye:
Renderer with more foveation

A foveation model with adjustable foveation level?

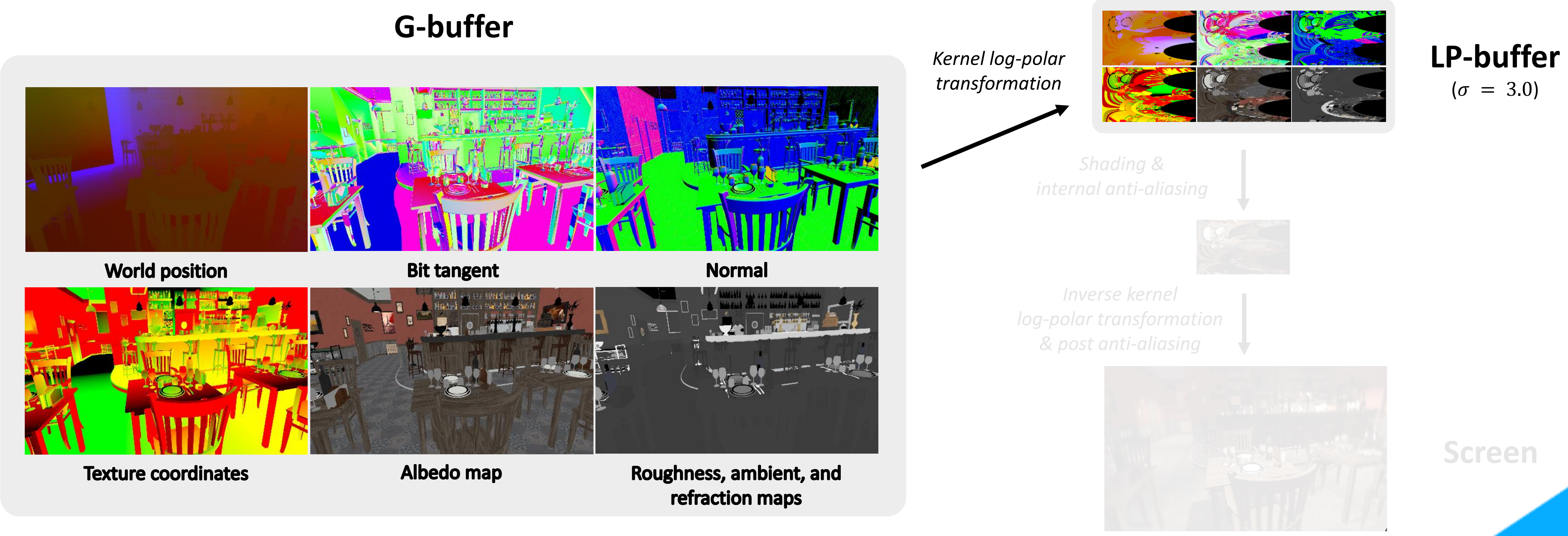
Kernel Foveation Model

A model with parameterized level of foveation



Kernel Foveation Model

A model with parameterized level of foveation



Kernel Foveation Model

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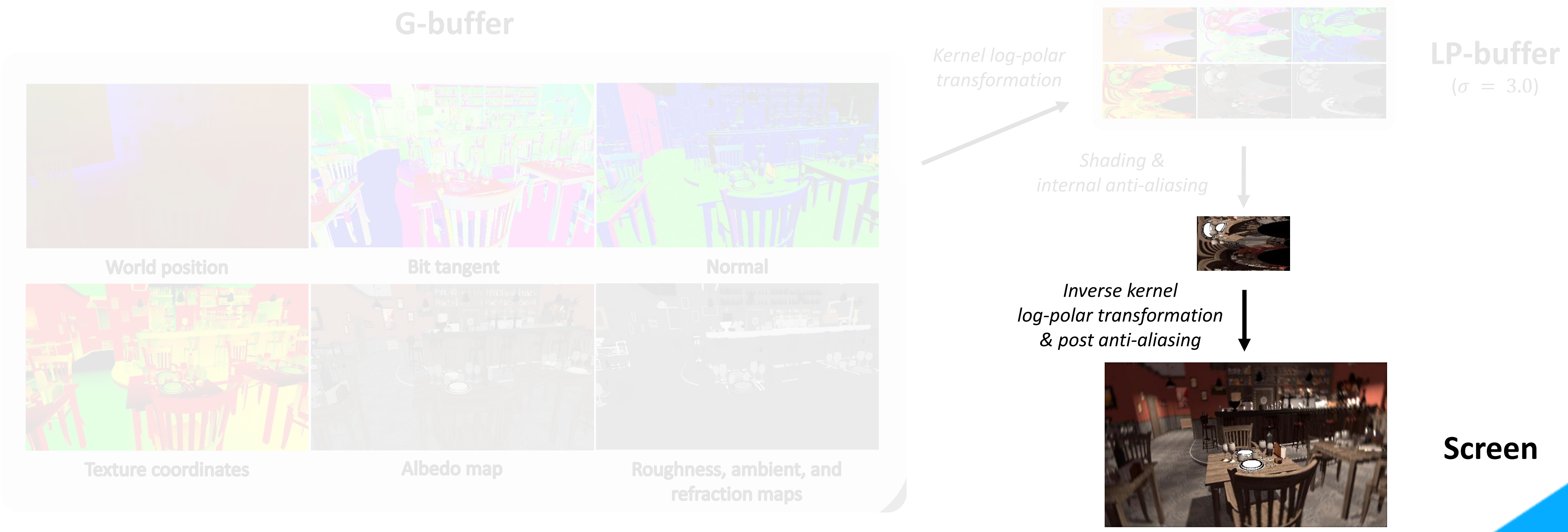
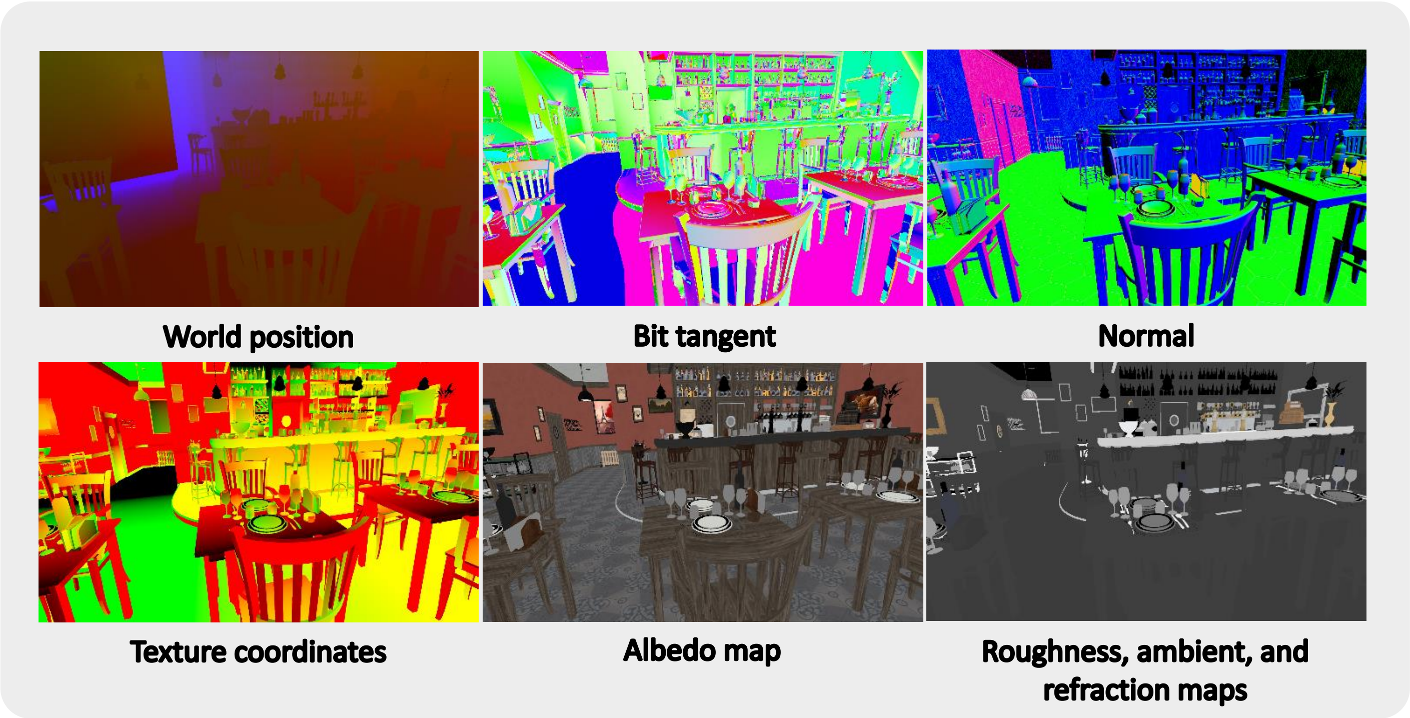
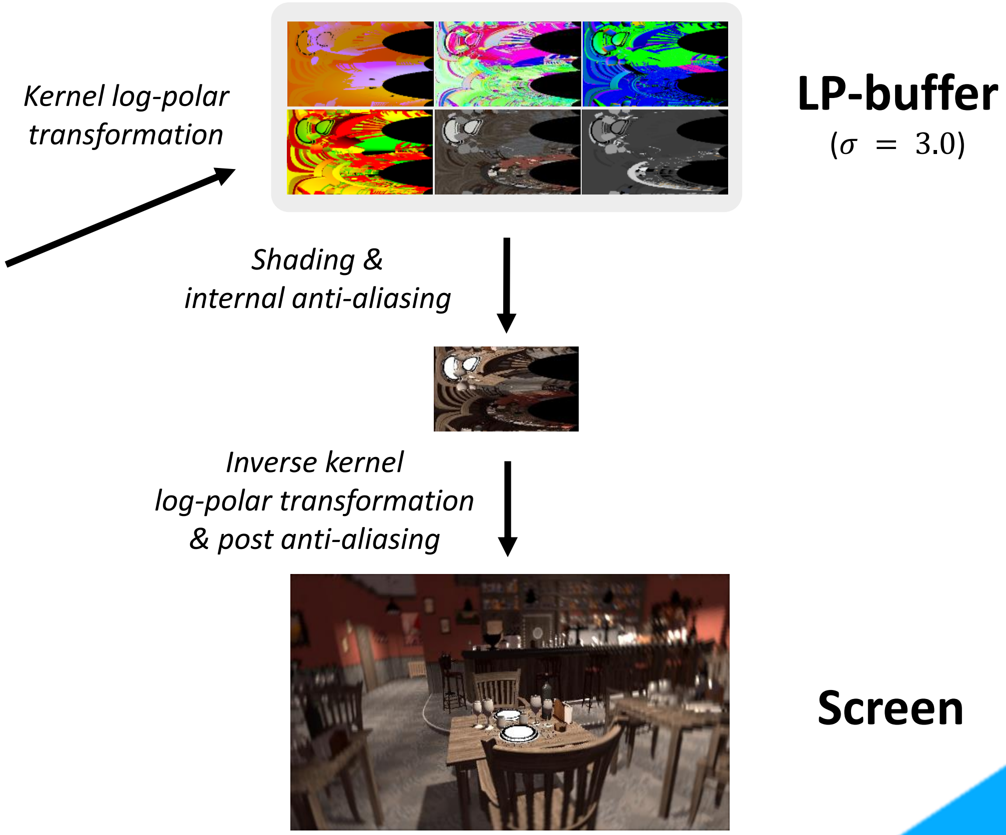


Kernel Foveation Model

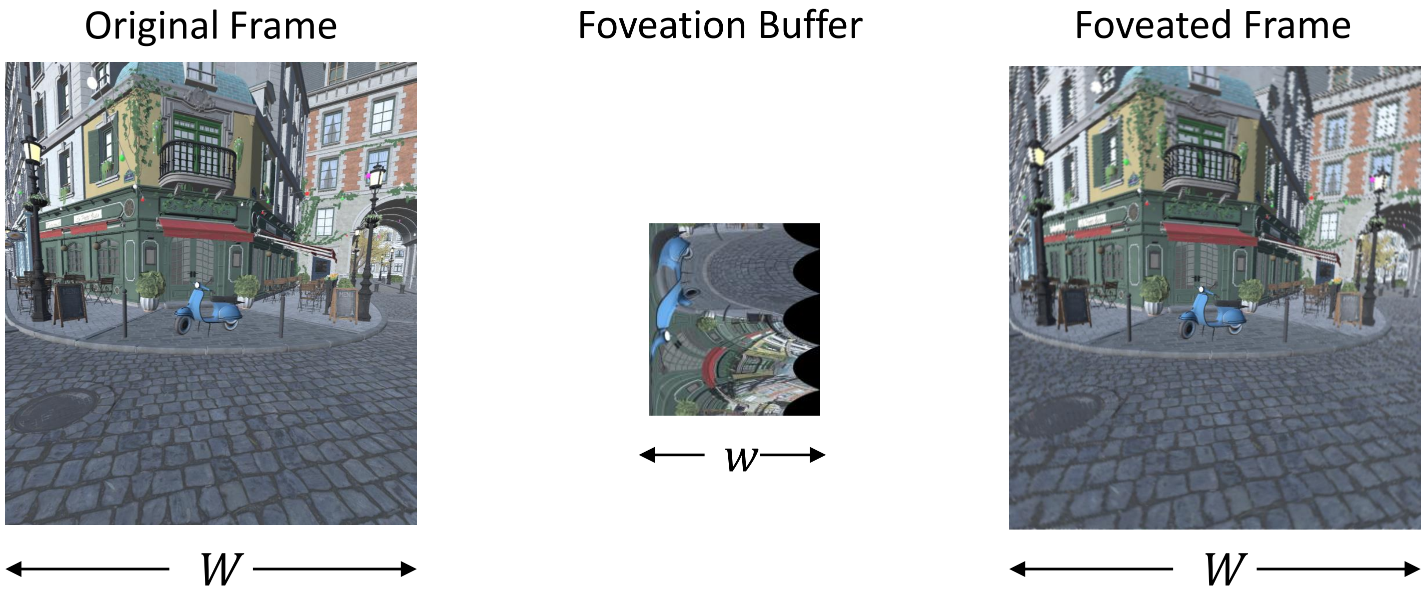
A model with parameterized level of foveation

G-buffer





Kernel Foveation Model

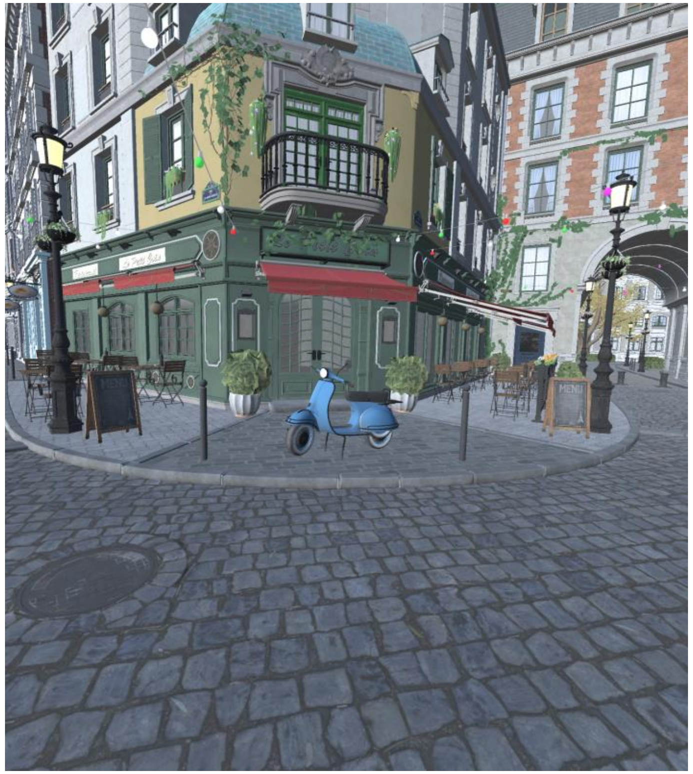


Kernel log-polar Mapping

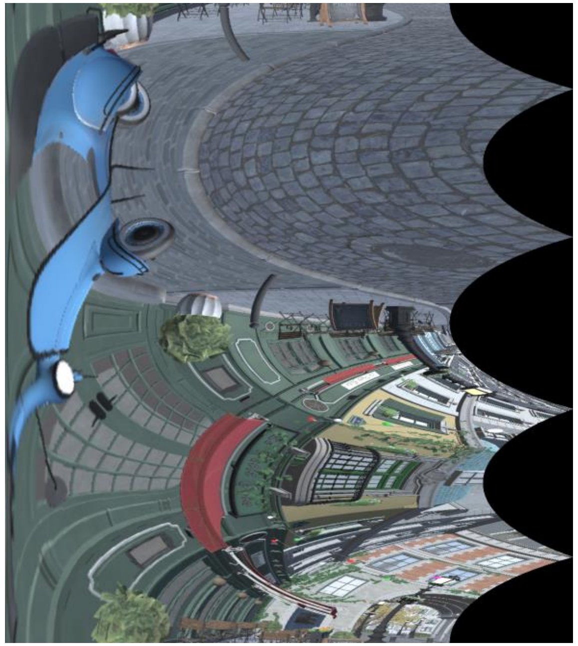
- *Buffer parameter* $\sigma = \frac{W}{w}$
- *Regular rendering time:* $t_{RR} = T$
- *Kernel foveated rendering time:* $t_{KFR} = \frac{T}{\sigma^2}$

Kernel Foveation Model

A model with parameterized level of foveation



Regular Rendering

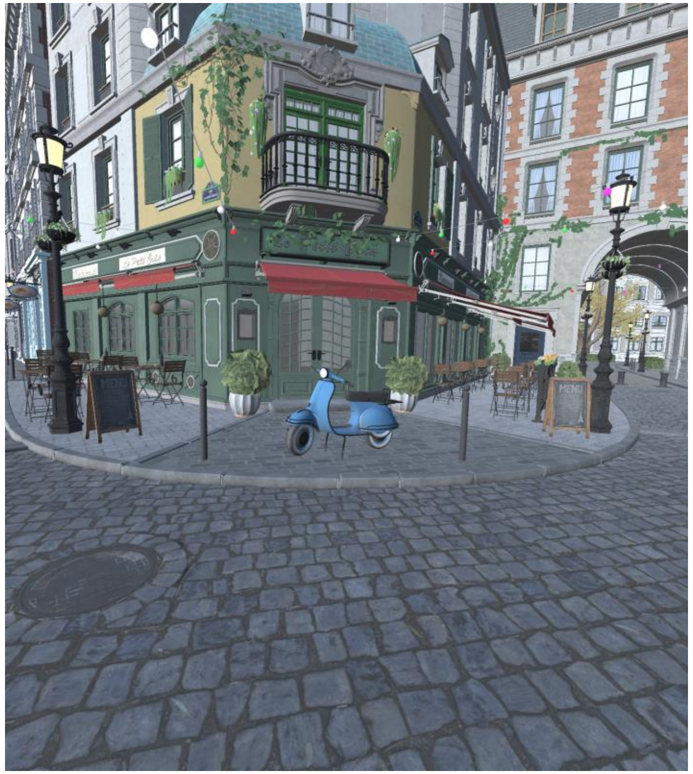


LP-buffer
$\sigma = 1.2$

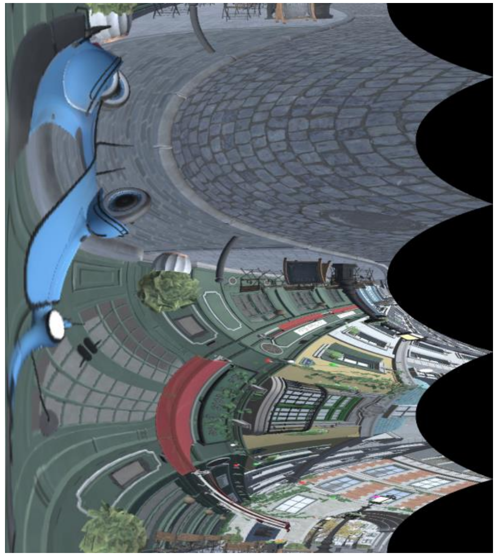
Foveated Rendering
(without anti-aliasing)

Kernel Foveation Model

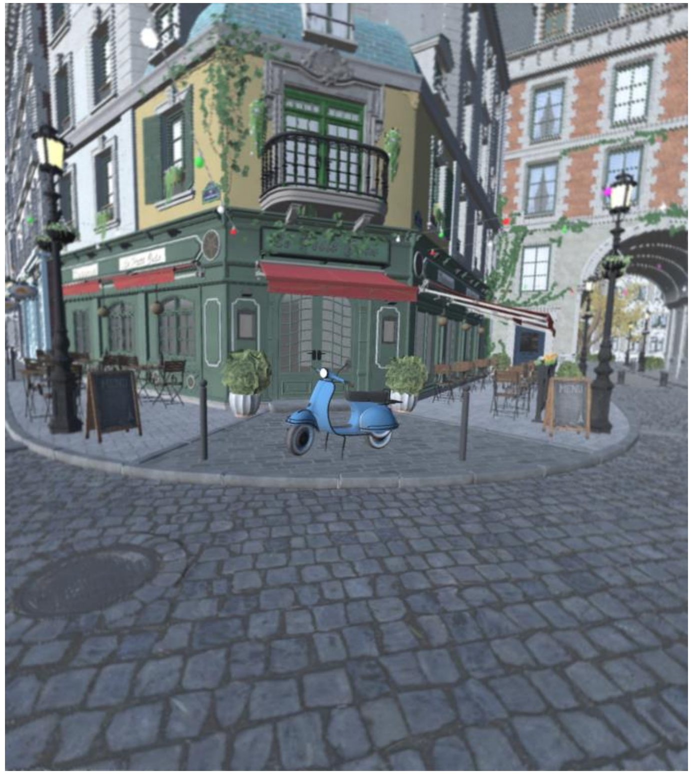
A model with parameterized level of foveation



Regular Rendering



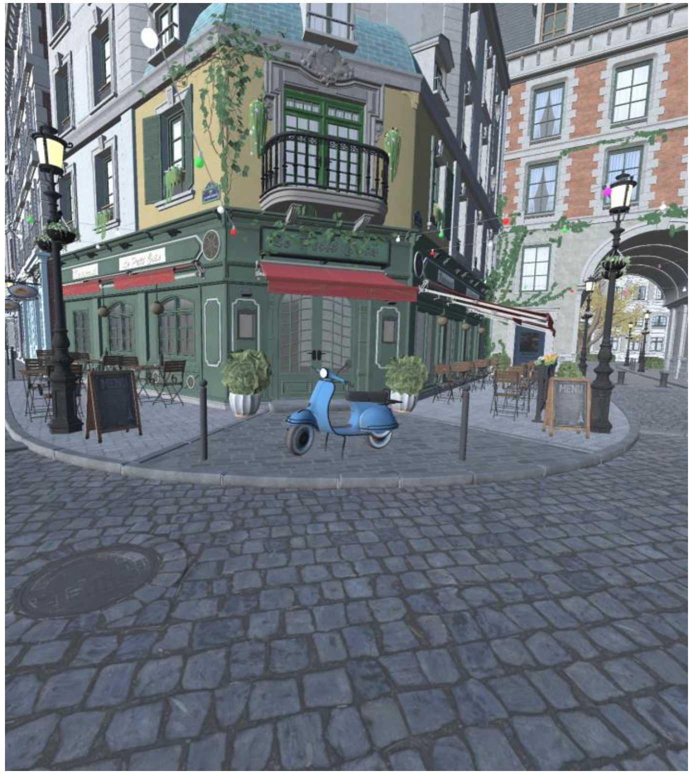
LP-buffer
$\sigma = 1.4$



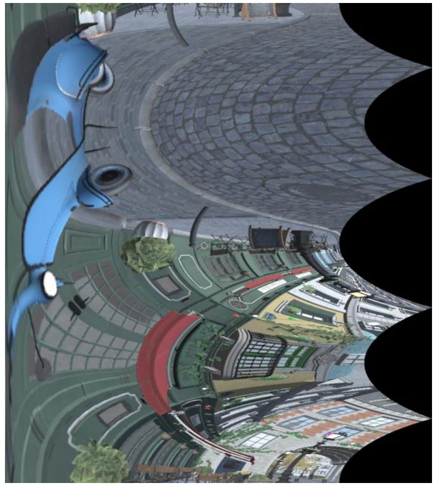
Foveated Rendering
(without anti-aliasing)

Kernel Foveation Model

A model with parameterized level of foveation



Regular Rendering

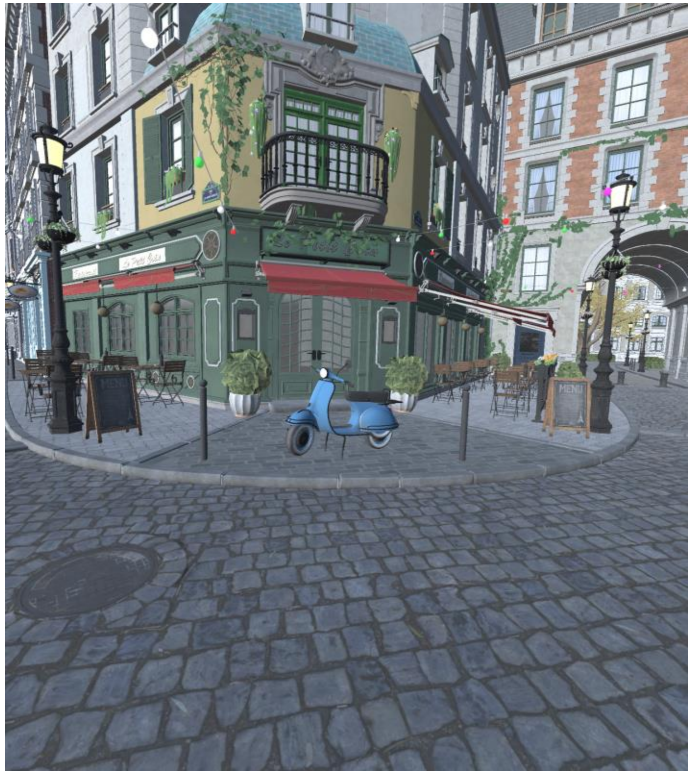


LP-buffer
$\sigma = 1.6$

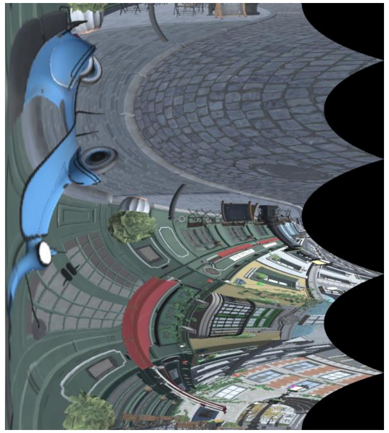
Foveated Rendering
(without anti-aliasing)

Kernel Foveation Model

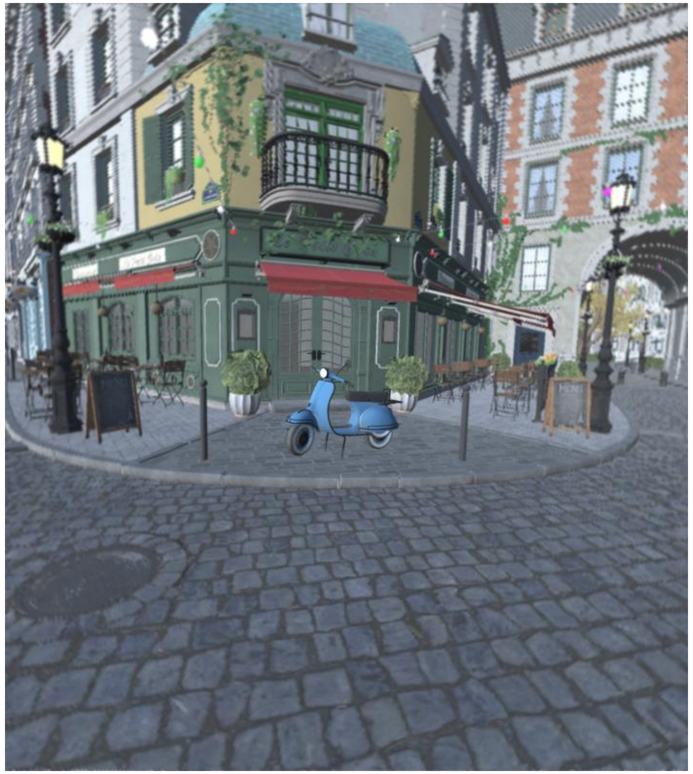
A model with parameterized level of foveation



Regular Rendering



LP-buffer
$\sigma = 1.8$



Foveated Rendering
(without anti-aliasing)

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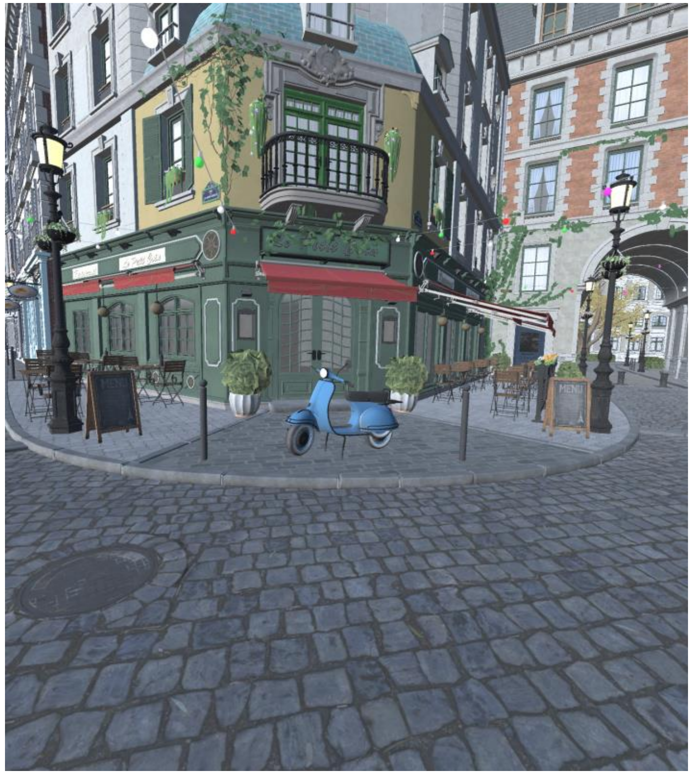
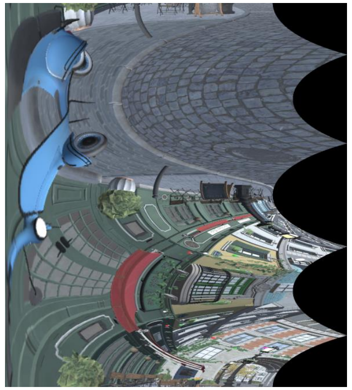
Kernel Foveation Model

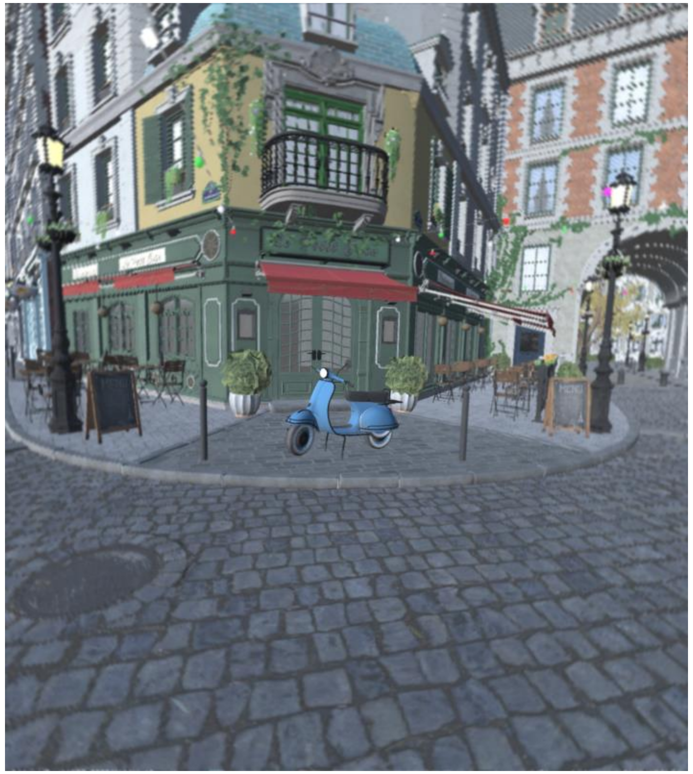
A model with parameterized level of foveation



Regular Rendering



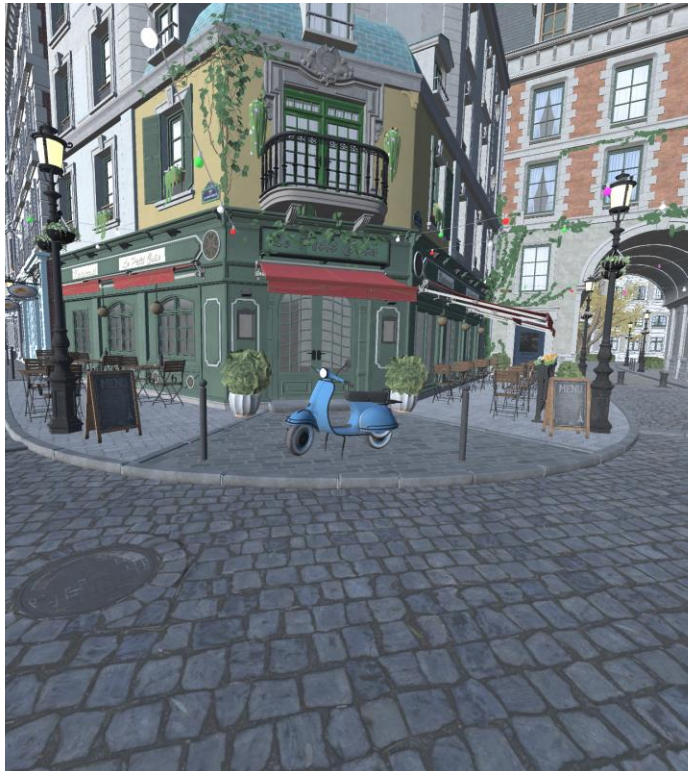
LP-buffer
$\sigma = 2.0$



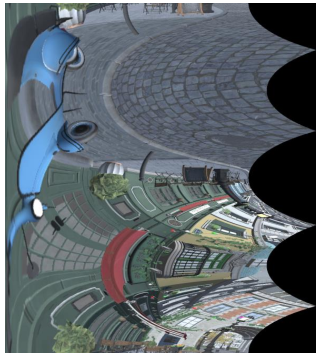
Foveated Rendering
(without anti-aliasing)

Kernel Foveation Model

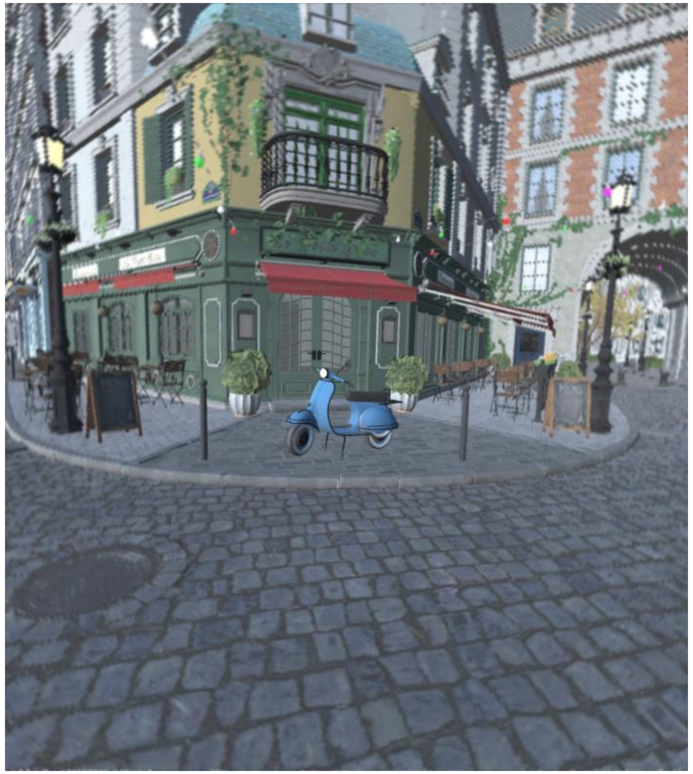
A model with parameterized level of foveation



Regular Rendering



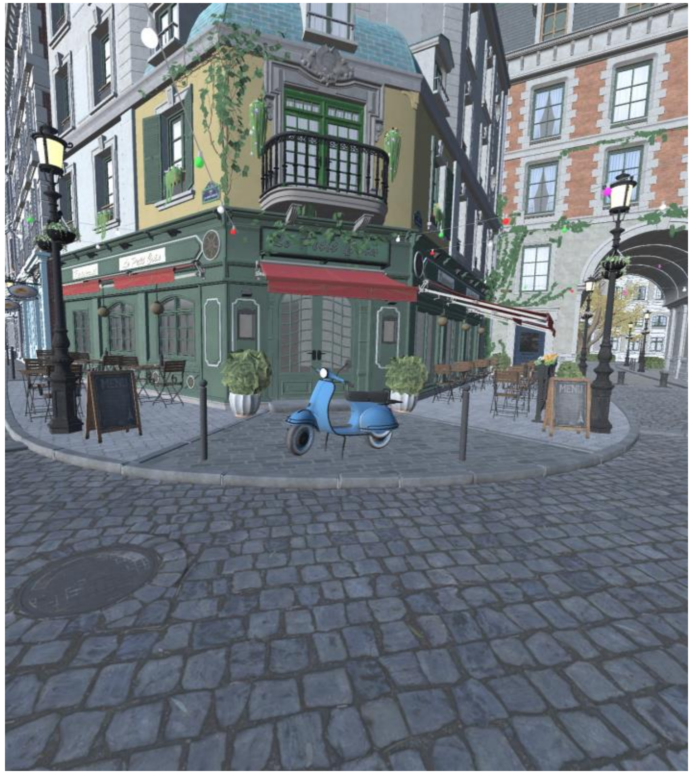
LP-buffer
$\sigma = 2.2$



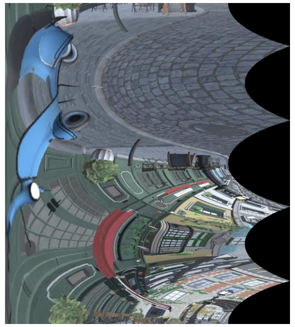
Foveated Rendering
(without anti-aliasing)

Kernel Foveation Model

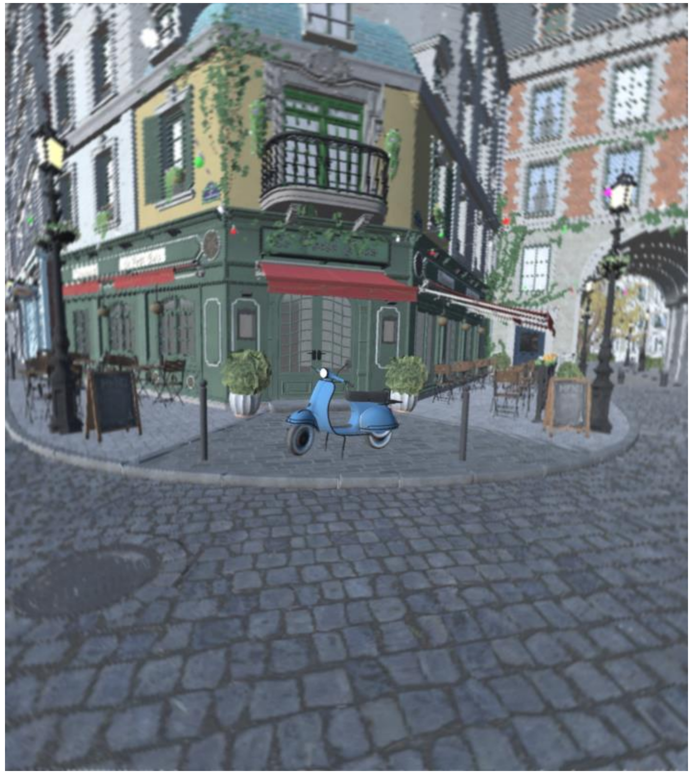
A model with parameterized level of foveation



Regular Rendering



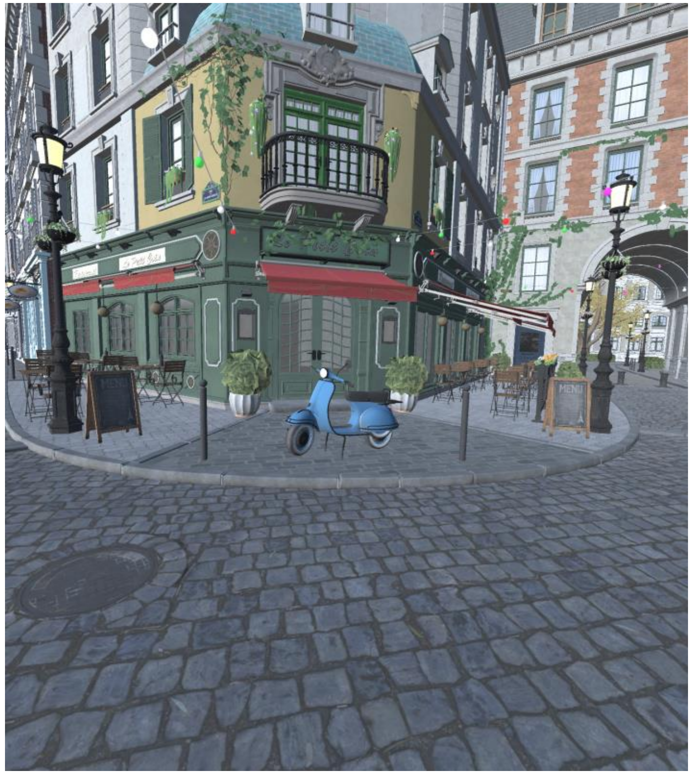
LP-buffer
$\sigma = 2.4$



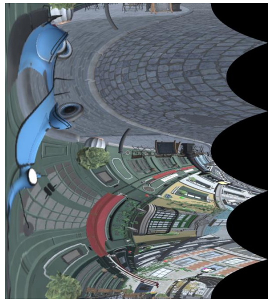
Foveated Rendering
(without anti-aliasing)

Kernel Foveation Model

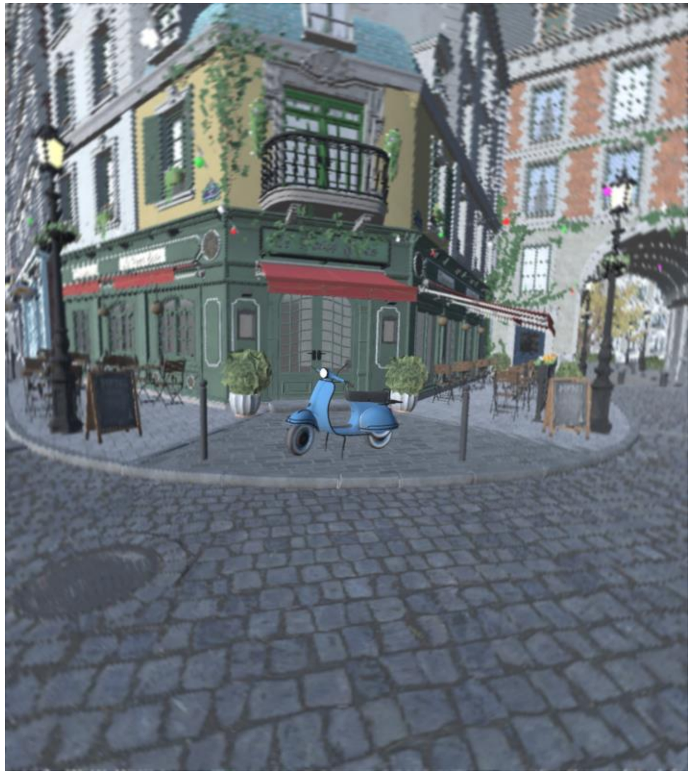
A model with parameterized level of foveation



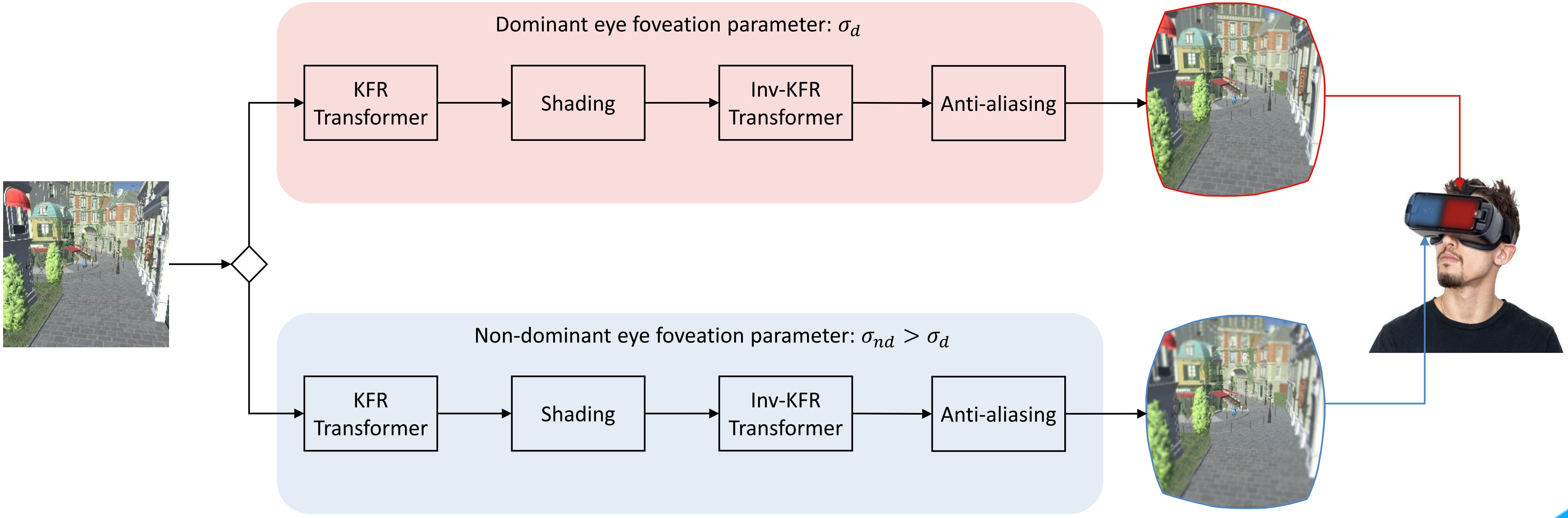
Regular Rendering



LP-buffer
$\sigma = 2.6$



Foveated Rendering
(without anti-aliasing)



Dominant eye foveation parameter: σ_d
KFR Transformer
Shading
Inv-KFR Transformer
Anti-aliasing
Non-dominant eye foveation parameter: $\sigma_{nd} > \sigma_d$
KFR Transformer
Shading
Inv-KFR Transformer
Anti-aliasing

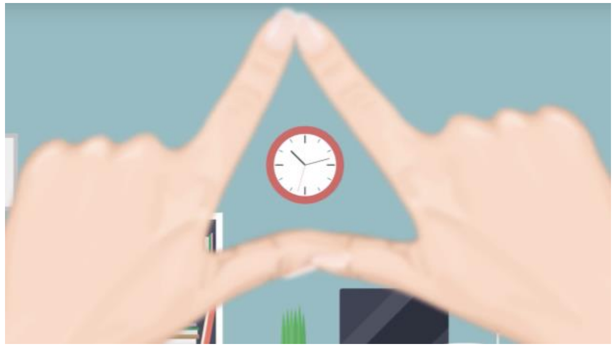
User Study

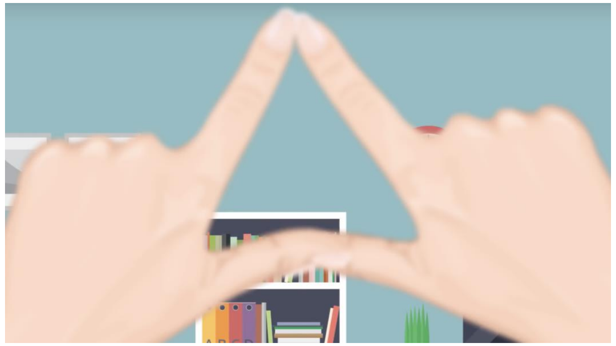
Apparatus

Pre-experiment: Dominant Eye Identification

The Miles Test

- the participant (TP) extends their arms out in front of himself
- creates a triangular opening between their thumbs and forefingers
- with both eyes open, TP centers the triangular opening on a goal object that is 20 feet away from TP
- TP closes their left eye with their right eye open, and the object moves out of center
  - Left eye dominant
- TP closes their right eye with their left eye open, and the object moves out of center
  - Right eye dominant





Main Study

Step 1: The participant estimates the *Uniform Foveation Parameter* σ_{UF}

Step 2: The participant estimates the *Non-dominant Eye Foveation Parameter* σ_{NF}

Step 3: The participant evaluates the quality of EFR with σ_{UF} and σ_{NF} by comparing with RR and KFR

EFR: eye-dominance-guided foveated rendering
KFR: traditional foveated rendering
RR: regular rendering

Main Study

Step 1: The participant estimates the *Uniform Foveation Parameter* σ_{UF}

↓

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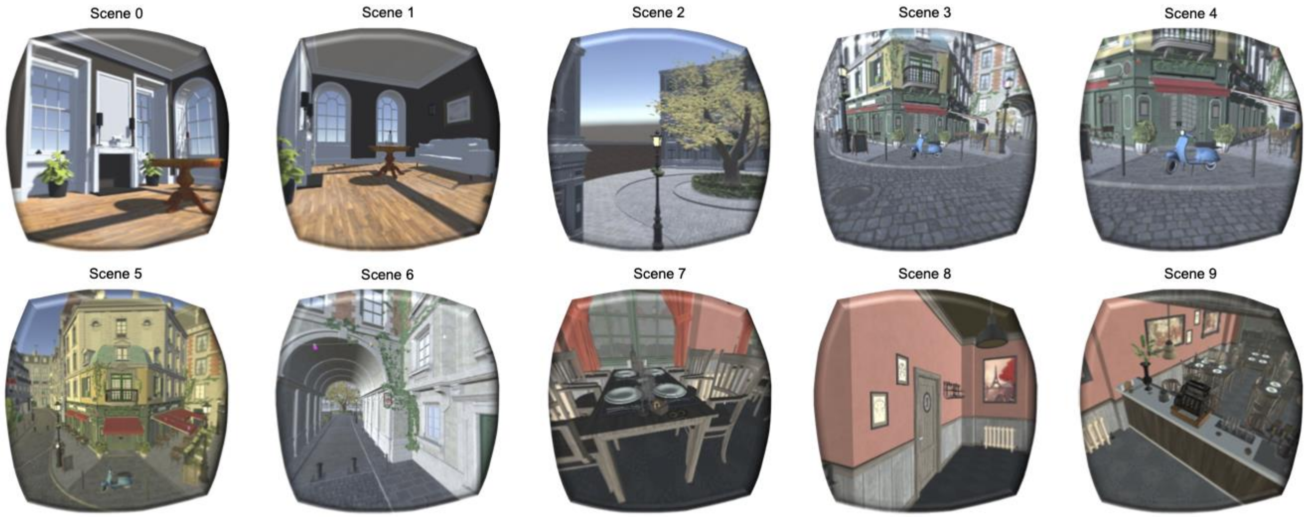


scenes for the user study
3 scenes for Step 1 & Step 2, 10 scenes for Step 3

Main Study

- Two tests in the main study:
  - Slider Test
  - Random Test
- Each test is repeated 3 times for each participant to reduce inaccuracy in parameter estimation.

Main Study

- Two tests in the main study:
  - Slider Test
  - Random Test
- Each test is repeated 3 times for each participant to reduce inaccuracy in parameter estimation.
- $\sigma = \frac{W}{w}$ (W: width of the screen, w: width of the rendering buffer)
  - Step 1 (Estimation of *Uniform Foveation Parameter* σ_{UF}):
    - MIN = 1.2
    - MAX = 3.0
    - STEP_SIZE = 0.2
  - Step 2 (Estimation of *Non-dominant Eye Foveation Parameter* σ_{NF}):
    - MIN = σ_{UF}
    - MAX = 4.0
    - STEP_SIZE = 0.2

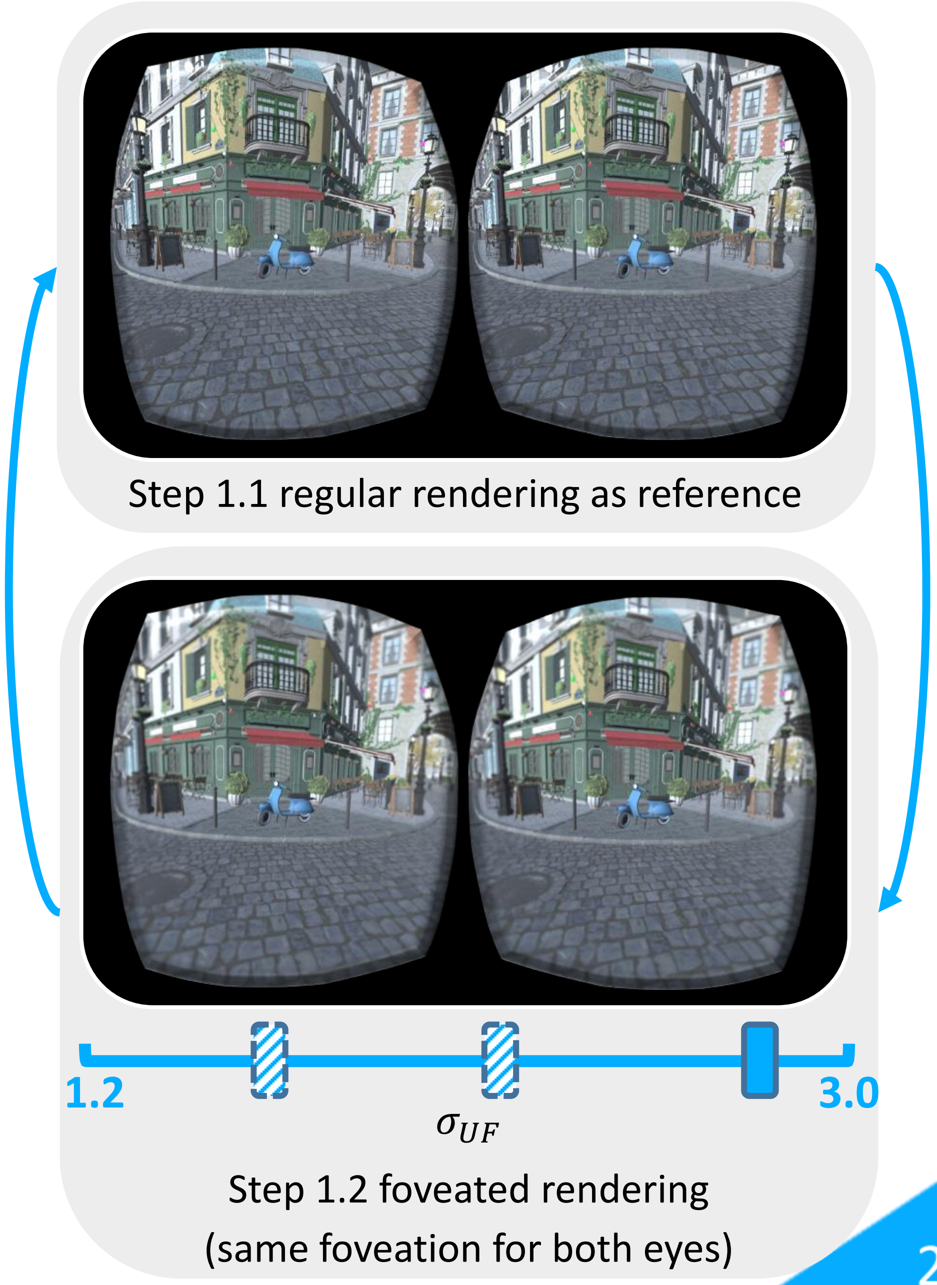
User Study

Main Study - Slider Test

Slider Test

Step 1: Estimation of σ_{UF}

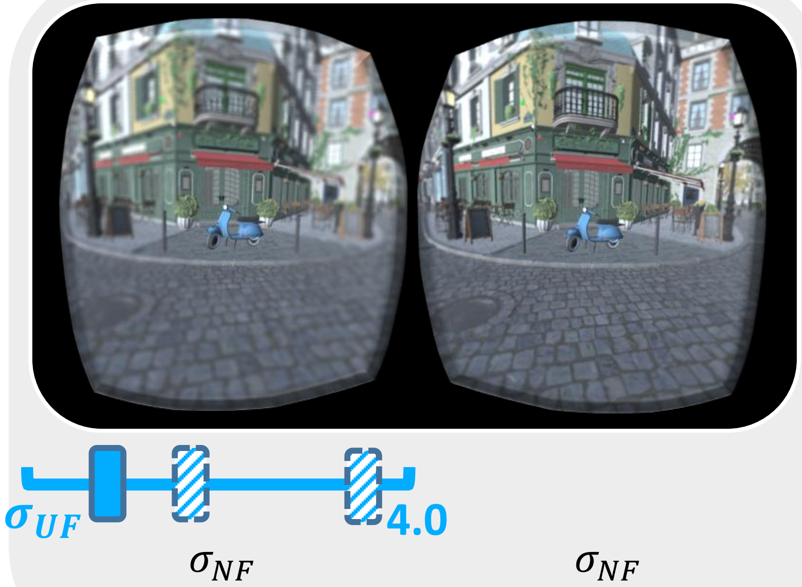
- Step 1.1: Present the participant with the regular rendering as a reference
- Step 1.2: Present the participant with the same foveated rendering for both eyes and allow the participant to adjust the level of foveation by themselves
  - starting with the highest level of foveation
  - progressively decrease the foveation level
- The participant switches between Step1.1 and Step 1.2 back and forth until he/she can identify the lowest foveation σ_{UF}



Slider Test

Step 2: Estimation of σ_{NF}

- Step 2: Present the participant foveated rendering with σ_{UF} for the **dominant eye**, allow the participant to adjust the foveation level for the **non-dominant eye**
  - starting with foveation parameter σ_{UF}
  - progressively increase the foveation level
- The participant finds the highest foveation level σ_{NF} that is perceptually equivalent to the result in Step 1



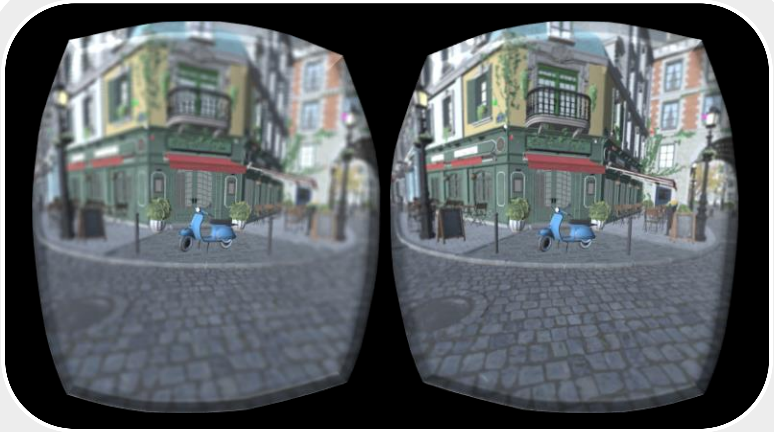
Step 2 foveated rendering

Slider Test

Step 3: Quality Evaluation

- The participant compares between
  - EFR vs. KFR
  - EFR vs. RR
- the participant scores the difference between the two frames
  - Max score = 5 (Same)
  - Min score = 1 (Noticeable Difference)

regular rendering



σ_{NF} σ_{UF}

Eye-dominance-guided foveated rendering

Choose a score for the difference between the two renderings?

1 2 3 4 5

User Study

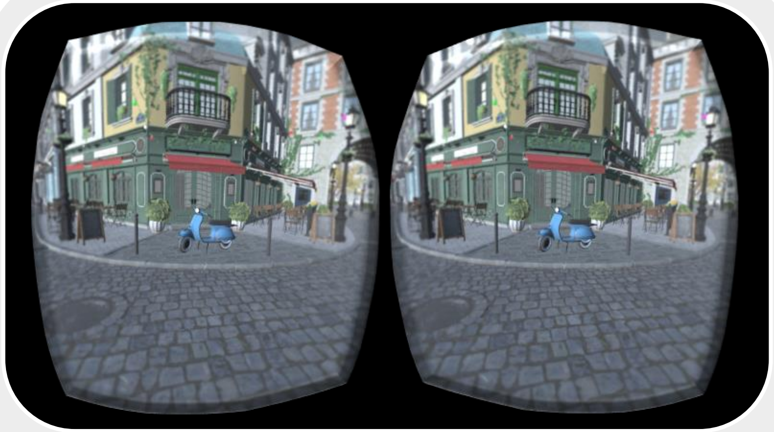
Main Study - Random Test

Random Test

Step 1: Estimation of σ_{UF}

- shuffled parameter array [1.2, 3.0]
- The participant observes the regular rendering & traditional foveated rendering with x selected from shuffled parameter array
- The participant scores the difference between the two frames $S_{UF}(x)$
  - Max score = 5 (Same)
  - Min score = 1 (Noticeable Difference)
- $\sigma_{UF} = \underset{x}{\operatorname{argmax}} S_{UF}(x) \geq 4$

regular rendering



σ_{UF} σ_{UF}

kernel foveated rendering

Choose a score for the difference between the two renderings?

1 2 3 4 5

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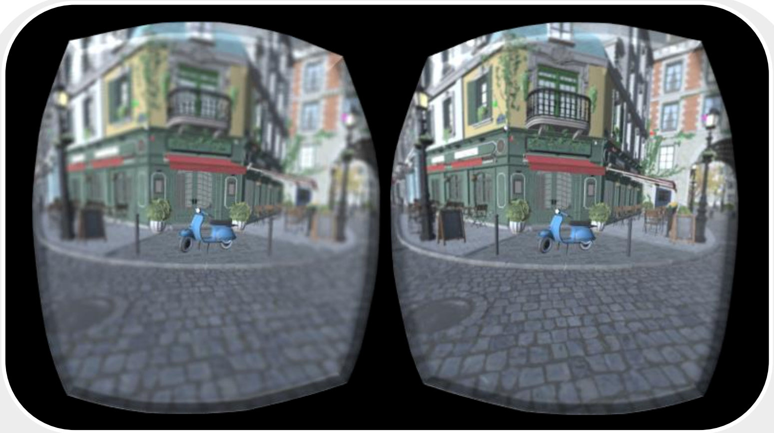
Random Test

Step 2: Estimation of σ_{NF}

- shuffled parameter array $[\sigma_{UF}, 4.0]$
- The participant observes eye-dominance-guided foveated rendering
  - Dominant eye rendered with σ_{UF}
  - Non-dominant eye rendered with x selected from shuffled parameter array
- the participant scores the imbalance between the two frames $S_{UF}(x)$
  - Max score = 5 (Same)
  - Min score = 1 (Noticeable Imbalance)
- $\sigma_{NF} = \underset{x}{\operatorname{argmax}} S_{NF}(x) \geq 4$



σ_{NF} σ_{UF}

Eye-dominance-guided foveated rendering

Choose a score for the difference between the two renderings?

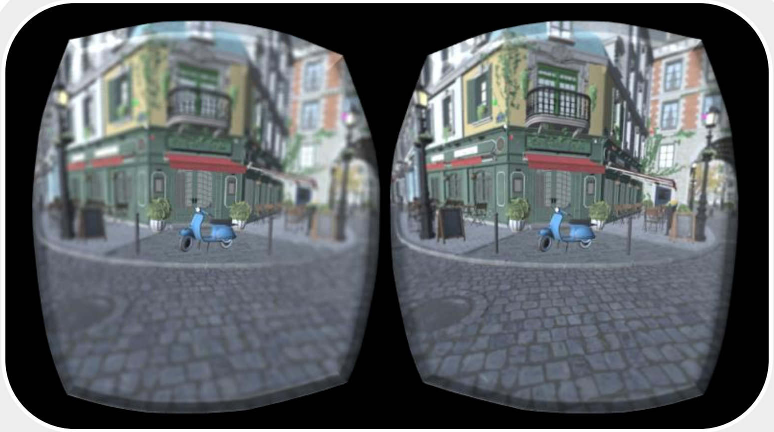
1 2 3 4 5

Random Test

Step 3: Quality Evaluation

- The participant compares between
  - EFR vs. KFR
  - EFR vs. RR
- the participant scores the difference between the two frames
  - Max score = 5 (Same)
  - Min score = 1 (Noticeable Difference)

regular rendering



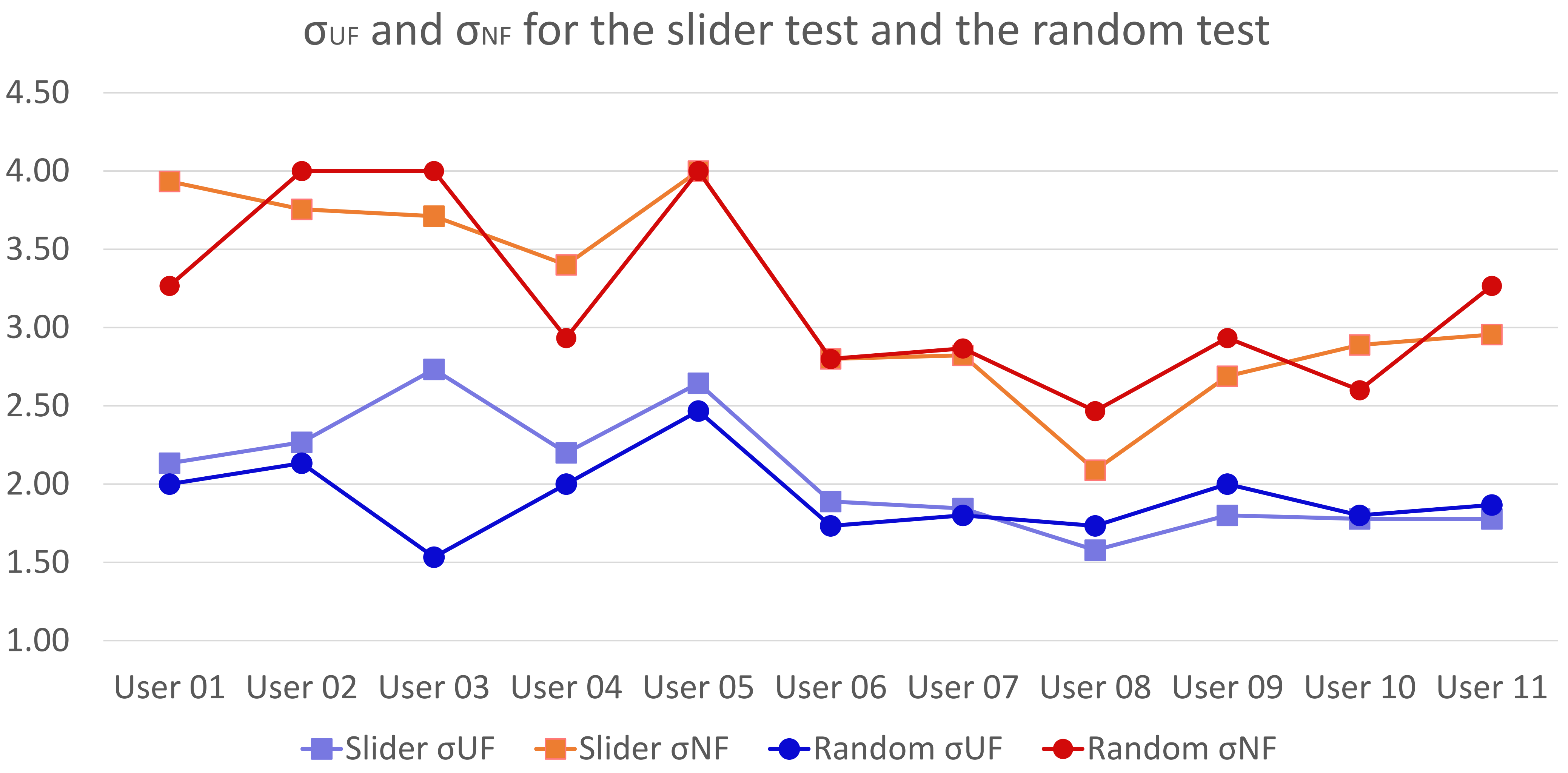
σ_{NF} σ_{UF}

Eye-dominance-guided foveated rendering

Choose a score for the difference between the two renderings?

1 2 3 4 5

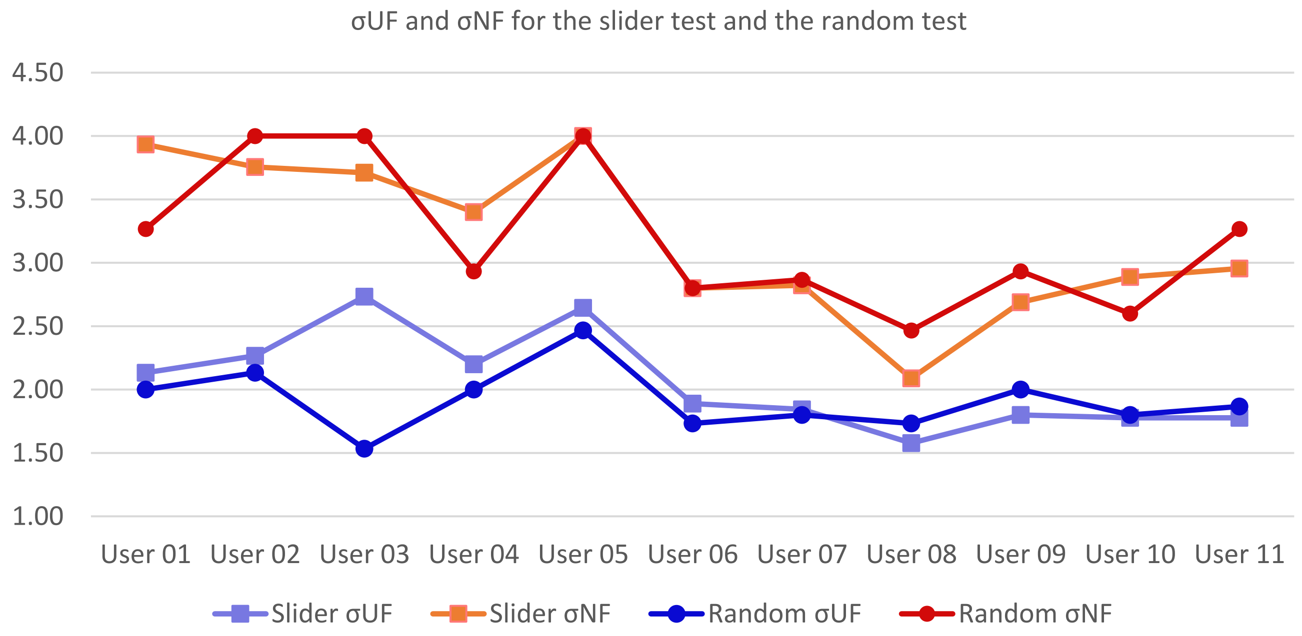
User Study Result


σUF and σNF for the slider test and the random test
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
User 01
User 02
User 03
User 04
User 05
User 06
User 07
User 08
User 09
User 10
User 11
Slider σUF
Slider σNF
Random σUF
Random σNF

Analysis: Relationship between σ_{UF} and σ_{NF}

Is there a significant difference of σ_{UF} and σ_{NF} between the slider test and the random test?

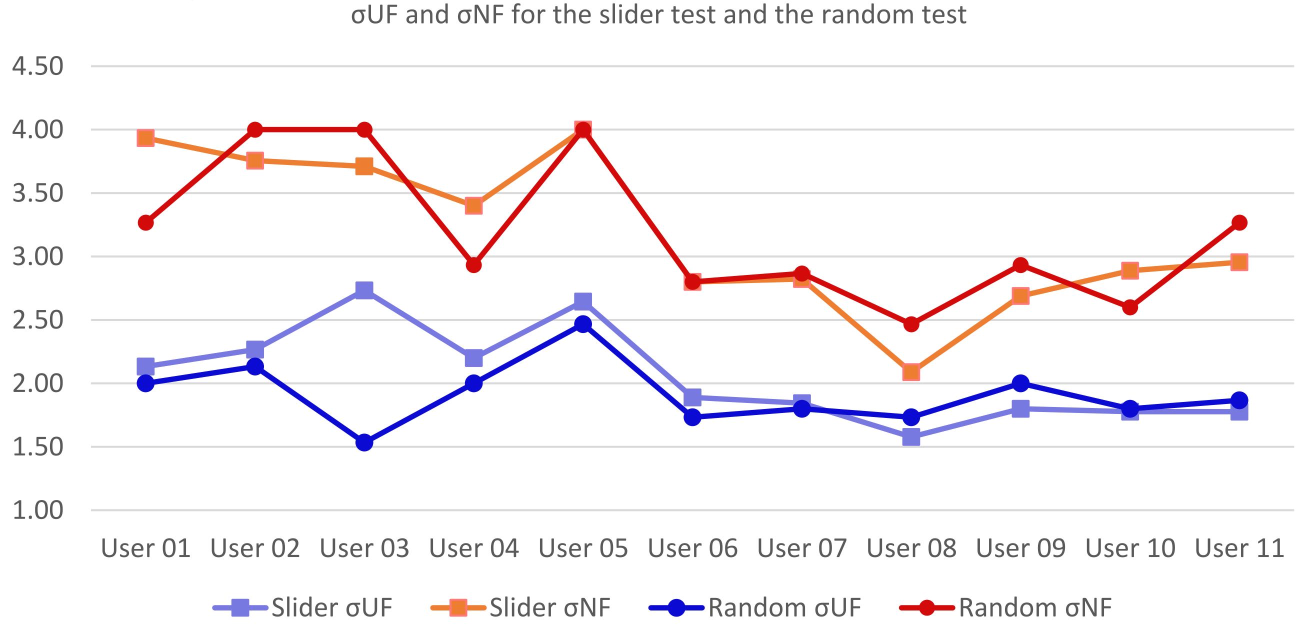
- Null hypothesis
  - there is no significant difference of σ_{UF} and σ_{NF} between the slider test and the random test
- Paired T-test
  - No significant difference between the slider test and the random test (with $p = 0.8995 > 0.05$)



Analysis: Relationship between σ_{UF} and σ_{NF}

Is there a significant difference between σ_{UF} and σ_{NF}?

- Null hypothesis
  - there is no significant difference between σ_{UF} and σ_{NF}
- Paired T-test
  - Significant difference that the foveation parameter σ_{NF} required for the non-dominant eye is higher than the foveation parameter σ_{UF} for the dominant eye (with $p = 7.0530 \times 10^{-10} < 0.05$)



Quality Evaluation

Score frequency in the slider test and the random test

Comparison	Score = 1	Score = 2	Score = 3	Score = 4	Score = 5
Slider: EFR vs. RR	0.00%	2.73%	8.18%	17.27%	71.82%
Slider EFR vs. KFR	0.00%	4.55%	10.91%	30.00%	54.55%
Random: EFR vs. RR	0.00%	0.00%	0.91%	14.55%	84.55%
Random: EFR vs. KFR	0.00%	0.91%	3.64%	25.45%	70.00%

Slider Test: $P(\text{score} \geq 4) \geq 85\%$
Random Test: $P(\text{score} \geq 4) \geq 95\%$

Rendering Acceleration

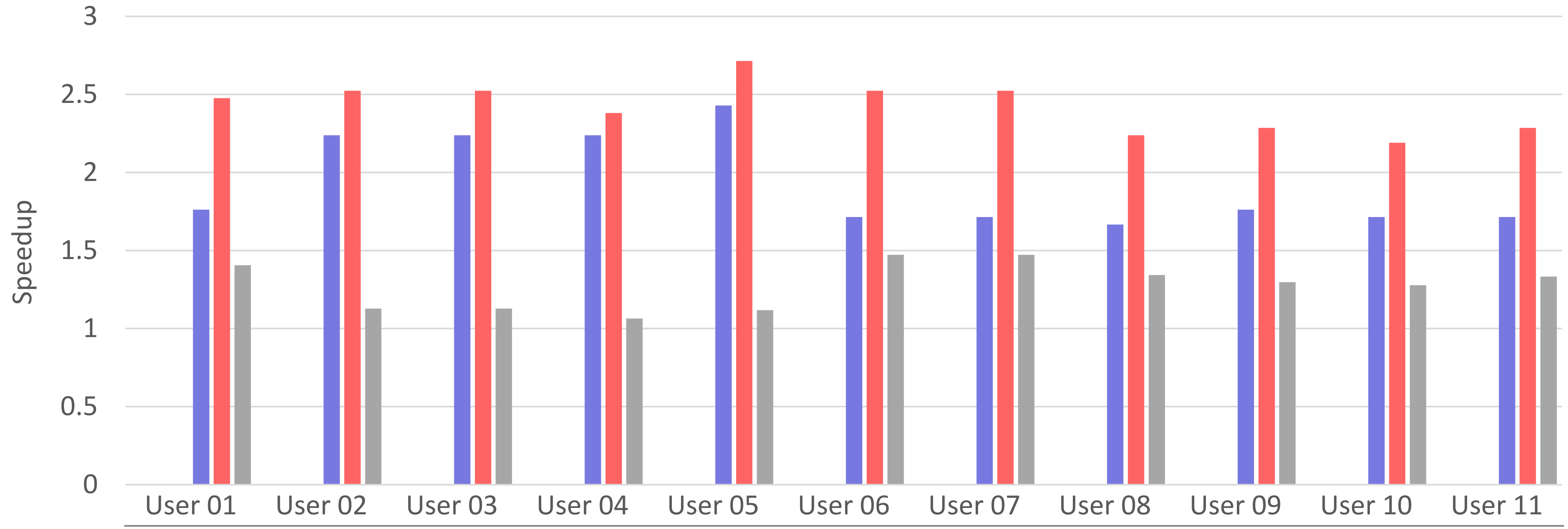
Rendering Acceleration

Setup

- GPU: NVIDIA GTX 1080
- *Scene: Amazon Lumberyard Bistro*
- Resolution: 1280 × 1440 per eye

RR = Regular Rendering
KFR = Kernel Foveated Rendering
EFR = Eye-dominance-guided Foveated Rendering

Speedup of eye-dominance-guided foveated rendering



	User 01	User 02	User 03	User 04	User 05	User 06	User 07	User 08	User 09	User 10	User 11
RR (fps)	21	21	21	21	21	21	21	21	21	21	21
KFR (fps)	37	47	47	47	51	36	36	35	37	36	36
EFR (fps)	52	53	53	50	57	53	53	47	48	46	48
Speedup (KFR vs. RR)	1.76	2.24	2.24	2.24	2.43	1.71	1.71	1.67	1.76	1.71	1.71
Speedup (EFR vs. RR)	2.48	2.52	2.52	2.38	2.71	2.52	2.52	2.24	2.29	2.19	2.29
Speedup (EFR vs. KFR)	1.41	1.13	1.13	1.06	1.12	1.47	1.47	1.34	1.30	1.28	1.33

Speedup (KFR vs. RR) Speedup (EFR vs. RR) Speedup (EFR vs. KFR)

Limitations

Limitations & Future Work

- Temporal Artifacts
  - since the eye-dominance-guided foveated rendering relies on different levels of foveation for the two eyes, the pattern of the artifact may appear differently.
- Personalized VR Rendering
  - 70% of the population is right-eye dominant and 29% is left-eye dominant
- Further Leveraging Human Perception
  - exploring how the foveated rendering system could be integrated with the cyclopean eye to further improve the immersive viewing experience

Conclusion

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  - provides similar visual results as the original foveated rendering
  - higher rendering frame rate

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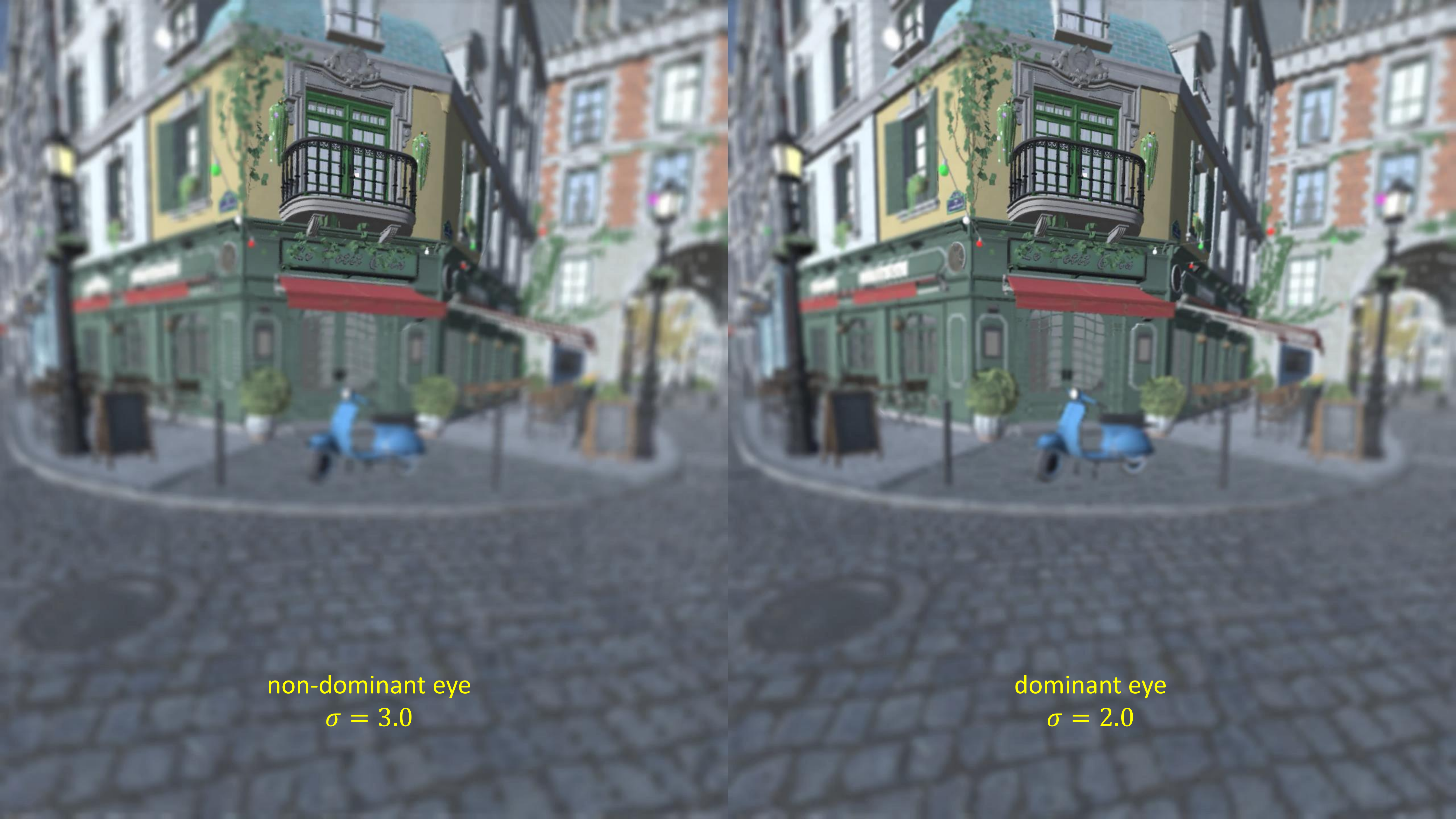
  - Parameters estimated from different user study show no significant difference
  - P(minimal perceptual difference) ≥ 85%

Conclusion

- designing eye-dominance-guided foveated rendering
  - provides similar visual results as the original foveated rendering
  - higher rendering frame rate
- conducting user studies to identify the parameters for the dominant eye and the non-dominant eye
  - Parameters estimated from different user study show no significant difference
  - P(minimal perceptual difference) ≥ 85%
- implementing the eye-dominance-guided foveated rendering pipeline on a GPU at a resolution of 1280 × 1440 per eye
  - Maximum speedup: 1.47×
  - Average speedup: 1.35×

Demo


non-dominant eye
$\sigma = 3.0$
dominant eye
$\sigma = 2.0$

Thank You

Analysis: Parameters Estimated with Different Scenes

Does the choice of scenes has effect on the feedback of the participants?

- Null hypothesis
  - the choice of scenes has no effect on the feedback of the participants
- One-way ANOVA test
  - No significant effect of the choice of scenes on the feedback (with $p = 0.9782 > 0.05$)

Analysis: Parameter Estimated with Different Tests

Is there a significant difference of σ_{UF} and σ_{NF} between the slider test and the random test?

- Null Hypothesis
  - there exists a significant difference of the quality evaluation results between the slider test and the random test.
- Paired T-test
  - No significant difference between the slider test and the random test (with $p = 0.8629 > 0.05$)

Analysis: Score Estimated with Different Comparison

Is there a significant difference between the experiment of EFR vs. KFR and the experiment of EFR vs RR?

- Null Hypothesis
  - there exists a significant difference between the experiment of EFR vs. KFR and the experiment of EFR vs RR.?
- Paired T-test
  - No significant difference between the slider test and the random test (with $p = 0.9410 > 0.05$)

Theoretical Speedup

Regular rendering per eye T

Regular rendering both eyes (RR) $t_{RR} = 2T$

Kernel foveated rendering with parameter σ_d:

$$t_{KFR} = \frac{T}{{\sigma_d}^2} + \frac{T}{{\sigma_d}^2} = \frac{2T}{{\sigma_d}^2}$$

Theoretical Speedup

Regular rendering per eye T

Regular rendering both eyes (RR) $t_{RR} = 2T$

Kernel foveated rendering with parameter σ_d:

$$t_{KFR} = \frac{T}{{\sigma_d}^2} + \frac{T}{{\sigma_d}^2} = \frac{2T}{{\sigma_d}^2}$$

Eye-dominance-guided with parameter σ_d (dominant eye) and σ_{nd} (non-dominant eye):

$$t_{EFR} = \frac{T}{{\sigma_d}^2} + \frac{T}{{\sigma_{nd}}^2} = \frac{T}{{\sigma_d}^2}(1 + (\frac{\sigma_d}{\sigma_{nd}})^2)$$

With $\sigma_{nd} \geq \sigma_d$,

$$(1 + (\frac{\sigma_d}{\sigma_{nd}})^2) \leq 2 \Rightarrow t_{EFR} \leq t_{KFR}$$

We can calculate the speedup:

$$S = \frac{t_{KFR}}{t_{EFR}} = \frac{2}{1 + (\frac{\sigma_d}{\sigma_{nd}})^2} \geq 1$$

Validation Test

- Eye Tracking Data Analysis
- Controlling for Lack of Attention and Exhaustion
  - Randomly inserted 30% of the trials to be validation trials in the random test
  - Estimation of σ_{UF}
    - presented TP with identical full-resolution rendering results for both comparison frames
  - Estimation of σ_{NF}
    - presented TP with identical rendering results with $\sigma_{UF} = \sigma_{NF}$ for both comparison frames
  - Validation
    - If the participant declared these validation trials to have a low score for similarity (3 or lower), we would ask TP to pause and take a break for at least 30 seconds, and then continue the user study
    - *If error* ≥ 5 in the random test, we would terminate the user study and discard the data of TP