Data Mining Pipeline Report

This report presents a comprehensive analysis of eye-tracking data, processed through a multi-stage pipeline designed to extract meaningful behavioral insights. The pipeline systematically cleans raw gaze data, identifies outliers, labels participant responses, and engineers features related to Areas of Interest (AOIs) and cognitive phases. The objective is to provide a robust framework for understanding user interaction patterns in response to presented stimuli, suitable for academic research and publication.

The analysis covers data from a total of **{n_participants} unique participants** and **{n_questions} unique questions**. Each stage of the pipeline is detailed below, including the methodologies applied, key variables computed, and the rationale behind the processing steps.

Overview

Unique participants: 23

Unique questions: 15

Stage 1 — Data Cleaning and Interaction Time (t_ij) Computation

Objective: This initial stage focuses on refining raw eye-tracking data by removing erroneous gaze samples and calculating the total interaction time for each participant-question pair.

Methodology:

- **Invalid Gaze Sample Removal:** Gaze samples are considered invalid and subsequently removed if their `BPOGV` (Binocular Point of Gaze Validity) value is not equal to 1, or if their gaze coordinates (`BPOGX`, `BPOGY`) are precisely (0,0). These conditions typically indicate data loss or tracking errors.
- **Interaction Time (t_ij) Computation:** For each unique combination of participant, question, and exam part, the total interaction duration, denoted as **t_ij**, is calculated. This metric represents the cumulative time a participant spent viewing a specific question. Following this, interactions shorter than 1 second are removed, as they are considered too brief to represent meaningful engagement.

Summary Statistics for t_ij: Mean = 57.41s, Median = 54.90s, Standard Deviation = 26.26s

Stage 2 — Fast Outlier Detection (Lower Bound - LB)

Objective: This stage identifies and flags unusually short interaction times (t_ij) that may represent superficial engagement or premature responses, using a statistical lower bound (LB) threshold.

Methodology:

- **Quartile and Interquartile Range (IQR) Computation:** For each unique question and exam part, the first quartile (Q1), median, third quartile (Q3), and Interquartile Range (IQR = Q3 - Q1) of the `t_ij` values are calculated. These statistics provide a robust measure of the central tendency and spread of interaction times, minimizing the influence of extreme values.
- **Lower Bound (LB) Calculation:** The Lower Bound (LB) is computed as $Q1 - 1.5 imes IQR$. This formula is a standard method for identifying potential outliers in a dataset, where values falling below the LB are considered statistically anomalous.
- **Time Validity Flagging:** An interaction is flagged as **`invalid_time`** if its `t_ij` value is less than the calculated `LB` for that specific question and part. This identifies interactions that are significantly shorter than the typical engagement duration.

Sample of Computed Thresholds (LB)

The table below shows a sample of the calculated Q1, Median, Q3, IQR, and LB values for different question-part combinations. These thresholds are crucial for identifying outliers in interaction times.

question_id	part	Q1	median	Q3	n_all	IQR	LB
Q1	Part 1	45.810300	58.309810	58.979770	5	13.169470	26.056095
Q1	Part 2	44.069695	55.883185	70.666438	14	26.596743	4.174581
Q10	Part 1	28.819580	30.792480	49.300080	3	20.480500	-1.901170
Q10	Part 2	54.819820	61.214720	71.706550	13	16.886730	29.489725
Q11	Part 1	38.397815	58.108855	79.377622	6	40.979807	-23.071896
Q11	Part 2	42.688960	52.529050	57.412590	9	14.723630	20.603515
Q12	Part 1	37.199770	37.832760	63.454225	7	26.254455	-2.181912
Q12	Part 2	35.208675	50.727480	65.870242	10	30.661567	-10.783676
Q13	Part 1	53.002750	65.487215	72.381453	4	19.378702	23.934696
Q13	Part 2	45.910760	57.003910	84.200620	9	38.289860	-11.524030
Q14	Part 1	37.789322	49.186890	63.218445	4	25.429123	-0.354361

question_id	part	Q1	median	Q3	n_all	IQR	LB
Q14	Part 2	38.116670	54.002930	68.842058	10	30.725387	-7.971411
Q15	Part 1	37.835790	43.331660	74.650630	7	36.814840	-17.386470
Q15	Part 2	24.991210	36.559810	44.865720	9	19.874510	-4.820555
Q2	Part 1	41.515492	57.888640	84.774867	6	43.259375	-23.373570
Q2	Part 2	30.727365	38.982730	49.778018	10	19.050653	2.151386
Q3	Part 1	49.308745	57.957765	76.604272	8	27.295527	8.365454
Q3	Part 2	50.429495	61.719080	68.450925	7	18.021430	23.397350
Q4	Part 1	64.509710	69.356260	85.431990	3	20.922280	33.126290
Q4	Part 2	42.213860	46.995020	58.558110	13	16.344250	17.697485

Stage 3 — Behavioral Labeling (Unusual/Normal Performance - UP/NP)

Objective: This stage assigns behavioral labels (Unusual Performance - UP, Normal Performance - NP, Invalid, or Not Applicable) to each participant's response based on their correctness and interaction time relative to a statistically derived upper fence.

Methodology:

- **Filtering for Valid Records:** Labeling is performed exclusively on records deemed valid from Stage 2 (i.e., not flagged as `invalid_time`).
- **Correct Answer Statistics (Q1_C, median_C, Q3_C, IQR_C):** Similar to Stage 2, quartile and IQR values are computed, but specifically for `t_ij` values associated with **only valid correct answers** for each question and part. This creates a baseline for efficient, correct responses.
- **Upper Fence for Correct Answers (UF_C):** The Upper Fence for Correct answers (UF_C) is calculated as $Q3_C + 1.5 imes IQR_C$. This threshold helps identify correct responses that took an unusually long time, potentially indicating a less efficient problem-solving process despite arriving at the correct answer.

Labeling Logic:

The following rules are applied sequentially to assign a behavioral label:

1. If `UF_C` cannot be computed (e.g., no valid correct answers for a given question/part), the label is set to `NA_no_correct` (Not Applicable - No Correct Answers).
2. If the participant's answer is **incorrect**, the label is set to `UP` (Unusual Performance).
3. If the participant's answer is **correct** but their `t_ij` is greater than `UF_C`, the label is also set to `UP` (Unusual Performance), indicating an unusually long time for a correct response.
4. In all other cases (correct answer and `t_ij` ≤ `UF_C`), the label is set to `NP` (Normal Performance).

Label Distribution

The distribution of assigned behavioral labels across all valid interactions is as follows:

label	count
UP	119
NP	95
NA_no_correct	14
INVALID	5

Sample of Thresholds for Correct Answers (UF_C)

This table provides a sample of the calculated Q1_C, Median_C, Q3_C, IQR_C, and UF_C values, derived exclusively from correct responses. These thresholds are used to differentiate between normal and unusual performance among correct answers.

question_id	part	Q1_C	median_C	Q3_C	n_correct_valid	IQR_C	UF_C
Q1	Part 1	58.644790	58.979770	68.767120	3	10.122330	83.950615
Q1	Part 2	228.007810	228.007810	228.007810	1	0.000000	228.007810
Q10	Part 1	28.819580	30.792480	49.300080	3	20.480500	80.020830
Q10	Part 2	55.168000	55.858220	70.350740	3	15.182740	93.124850
Q11	Part 1	65.950713	78.052915	83.346907	4	17.396195	109.441200
Q11	Part 2	45.145502	47.602045	50.058587	2	4.913085	57.428215
Q12	Part 1	36.715330	37.684210	84.541260	5	47.825930	156.280155
Q12	Part 2	24.597040	24.597040	24.597040	1	0.000000	24.597040
Q13	Part 1	65.487215	68.183410	76.579495	3	11.092280	93.217915

question_id	part	Q1_C	median_C	Q3_C	n_correct_valid	IQR_C	UF_C
Q13	Part 2	58.063780	70.216800	78.055425	3	19.991645	108.042892
Q14	Part 1	37.789322	49.186890	63.218445	4	25.429123	101.362129
Q14	Part 2	52.670410	58.236090	72.377380	5	19.706970	101.937835
Q15	Part 1	39.334495	58.999605	78.115475	4	38.780980	136.286945
Q15	Part 2	24.897950	24.991210	44.865720	5	19.967770	74.817375
Q2	Part 1	40.643872	68.136825	90.468530	4	49.824658	165.205516
Q2	Part 2	34.527135	45.783930	63.233275	3	28.706140	106.292485
Q3	Part 1	55.852662	65.389650	92.590157	6	36.737495	147.696400
Q3	Part 2	61.719080	62.723630	74.178220	5	12.459140	92.866930
Q4	Part 1	64.509710	69.356260	85.431990	3	20.922280	116.815410
Q4	Part 2	39.971193	46.132520	58.528963	8	18.557770	86.365617

Stage 4 — Area of Interest (AOI) Features & Cognitive Phases

Objective: This final processing stage extracts granular features related to specific Areas of Interest (AOIs) on the screen and delineates distinct cognitive phases (Reading and Answering) within each interaction.

Methodology:

- **Cognitive Phase Duration Computation:** The total interaction time (`t_ij`) is segmented into two primary cognitive phases: **Reading Duration** and **Answering Duration**. This segmentation is critical for understanding how participants allocate their attention during problem-solving.
    - **Question→Choice Transition:** The transition point from the Reading phase to the Answering phase is determined by identifying the first gaze sample that falls within any of the defined `Choice` AOIs after initially fixating on the `Question` AOI. If `BKID` (Button/Key ID) data is available, it is used to precisely mark the moment a participant interacts with an option.
    - **Midpoint Fallback:** In cases where AOI transition data or `BKID` is not available or ambiguous, a fallback mechanism is employed where the midpoint of the total `t_ij` is used to approximate the transition between reading and answering phases.
- **AOI Time Aggregation:** For each interaction, the cumulative gaze duration within predefined Areas of Interest (AOIs) is calculated. These AOIs typically include: `Question` (the question text area), `Choice_A`, `Choice_B`, `Choice_C`, `Choice_D` (individual answer options), `Timer` (the countdown timer area), and `Submit` (the submission button area). These aggregated times provide insights into attentional distribution.

Sample of Final Processed Features (Stage 4)

The table below displays a sample of the enriched dataset after Stage 4, including behavioral labels, phase durations, and aggregated AOI gaze times. These features form the basis for further in-depth analysis.

participant_id	question_id	part	t_ij	label	Reading_duration_s	Answering_duration_s	Question	Choice_A	Choice_B	Choice_C	Choice_D	Timer	Submit
participant_1	Q1	Part 2	175.19141	UP	75.39795	99.79346	89.19044	2.46047	2.98731	1.51268	0.23730	0.00000	0.0
participant_1	Q10	Part 2	85.02930	UP	63.14648	21.88282	34.31785	4.96877	7.86035	3.90968	5.08984	0.11816	0.0
participant_1	Q11	Part 2	37.12207	UP	18.01807	19.10400	15.61621	0.00000	0.47509	0.00000	0.00000	0.00000	0.0
participant_1	Q12	Part 2	84.43994	UP	35.72949	48.71045	26.89939	1.91650	1.19042	0.94189	0.67822	0.31494	0.0
participant_1	Q14	Part 1	82.24365	NP	6.45117	75.79248	53.05224	0.79785	0.52588	1.49415	0.61621	0.20801	0.0
participant_1	Q15	Part 2	44.86572	NP	22.41992	22.44580	12.68162	1.33885	2.22315	0.88380	0.30810	0.00000	0.0
participant_1	Q4	Part 2	32.05957	NP	23.64599	8.41358	9.84717	1.11230	0.00000	2.22265	0.16308	0.00000	0.0
participant_1	Q5	Part 1	79.48242	NA_no_correct	6.36914	73.11328	42.02001	0.73829	1.25926	0.36816	0.81007	0.00000	0.0
participant_1	Q6	Part 2	91.59570	UP	45.56250	46.03320	39.96582	5.85449	1.30665	1.46193	1.50488	0.52930	0.0
participant_1	Q9	Part 1	84.47266	UP	57.03711	27.69092	13.21044	1.64794	2.08398	1.71338	0.84424	0.48535	0.0
participant_10	Q10	Part 2	54.47778	NP	27.02844	27.44934	33.26595	0.77894	2.30401	0.16131	1.12476	0.00000	0.0
participant_10	Q11	Part 1	37.59235	NP	18.66156	18.93079	14.57801	0.35602	0.00000	0.86670	0.42206	0.10871	0.0
participant_10	Q12	Part 1	42.36719	UP	21.01923	21.34796	12.40683	3.11597	2.34991	0.53576	0.73632	0.00000	0.0
participant_10	Q14	Part 2	29.82794	UP	26.02277	3.80517	8.39649	0.00000	0.65582	0.70453	0.42152	0.00000	0.0
participant_10	Q15	Part 1	40.83320	NP	20.39679	20.43641	15.02144	0.18066	1.46771	0.28095	0.63702	0.26123	0.0
participant_10	Q2	Part 2	23.27034	NP	11.60155	11.66879	2.19786	6.30323	0.15537	1.29373	0.00000	0.00000	0.0
participant_10	Q3	Part 2	132.43420	UP	48.74388	83.69032	57.77601	2.41020	5.17435	0.79577	1.59511	0.00000	0.0
participant_10	Q4	Part 1	101.50772	NP	50.49939	51.00833	60.26283	2.86984	0.98617	0.48207	1.52591	0.00000	0.0
participant_10	Q6	Part 2	58.32938	UP	28.85715	29.47223	28.59945	2.21514	1.61481	2.75372	1.21298	0.27448	0.0
participant_10	Q7	Part 2	81.98227	UP	40.86740	41.11487	20.99789	13.15733	3.28691	3.99327	3.95969	0.00000	0.0

Key Variables and Definitions

This section provides a glossary of key variables and terms used throughout the data mining pipeline and in this report, crucial for a thorough understanding of the analysis.

- `**participant_id**`: A unique identifier assigned to each study participant.
- `**question_id**`: A unique identifier for each question presented to participants.
- `**part**`: Denotes the section of the exam (e.g., 'Part 1', 'Part 2') to which a question belongs.
- `**BPOGV**` **(Binocular Point of Gaze Validity)**: A metric indicating the validity of the recorded gaze sample. A value of 1 typically signifies valid gaze data.

- **`t_ij` (Interaction Time)**: The total duration, in seconds, that participant `i` spent interacting with question `j`.
- **`Q1`, `median`, `Q3`**: The first quartile, median, and third quartile of `t_ij` values, respectively, calculated per question and part.
- **`IQR` (Interquartile Range)**: The difference between the third and first quartiles (`Q3 - Q1`), representing the spread of the middle 50% of `t_ij` values.
- **`LB` (Lower Bound)**: A statistical threshold calculated as $Q1 - 1.5 imes IQR$, used to identify unusually short interaction times (outliers).
- **`invalid_time`**: A flag indicating that an interaction's `t_ij` fell below the `LB`, suggesting an outlier.
- **`is_correct`**: A binary variable (1 or 0) indicating whether the participant's answer to a question was correct.
- **`Q1_C`, `median_C`, `Q3_C`**: The first quartile, median, and third quartile of `t_ij` values, calculated exclusively for **correct answers** per question and part.
- **`IQR_C` (Interquartile Range for Correct Answers)**: The `IQR` calculated specifically for `t_ij` values of correct answers.
- **`UF_C` (Upper Fence for Correct Answers)**: A statistical threshold calculated as $Q3_C + 1.5 imes IQR_C$, used to identify unusually long interaction times for correct answers.
- **`label`**: The behavioral label assigned to each interaction:
  - `NP` (Normal Performance): Correct answer with `t_ij` within expected range.
  - `UP` (Unusual Performance): Incorrect answer, or correct answer with `t_ij` exceeding `UF_C`.
  - `INVALID`: Interaction flagged due to `invalid_time` in Stage 2.
  - `NA_no_correct`: Not Applicable, due to insufficient correct answers to compute `UF_C`.
- **`Reading_duration_s`**: The estimated time, in seconds, a participant spent reading the question and options.
- **`Answering_duration_s`**: The estimated time, in seconds, a participant spent actively considering and selecting an answer.
- **AOI (Area of Interest)**: Predefined regions on the screen (e.g., Question, Choice A, Timer, Submit) used to aggregate gaze data.

Notes

- If the background image is not available, the heatmap will be generated without a background.
- The coordinates for writing texts and rectangles on the background are read from `config.ini`; if not present, default values are used.

Overlay Coordinates (from config.ini)

No [Overlay] section found in config.ini — defaults used.

Per-stage Analysis Summary

This section provides a concise summary of key findings and statistics derived from each stage of the data processing pipeline.

Stage 1 — Data Cleaning & t_ij Computation Summary

Total Valid Interactions (post-cleaning): 233 records.

Interaction Time (t_ij) Statistics:

- Mean t_ij: 57.41 seconds
- Median t_ij: 54.90 seconds
- Standard Deviation of t_ij: 26.26 seconds

These statistics indicate the central tendency and variability of participant engagement times after initial data cleaning and filtering of very short interactions.

Stage 2 — Outlier Detection Summary

Number of Question-Part Groups with Computed Lower Bounds (LB): 30.

The outlier detection process identified interactions with unusually short durations, which are critical for understanding potentially disengaged or rushed responses. A sample of the computed LB thresholds is provided above.

Stage 3 — Behavioral Labeling Summary

Distribution of Behavioral Labels:

- **UP**: 119 instances.
- **NP**: 95 instances.
- **NA_no_correct**: 14 instances.
- **INVALID**: 5 instances.

This distribution provides a high-level overview of participant performance and engagement patterns, categorizing responses into Normal Performance (NP), Unusual Performance (UP), Invalid interactions, and cases where correct answer thresholds could not be established (NA_no_correct).

Stage 4 — AOI Features & Cognitive Phases Summary

Cognitive Phase Durations:

- **Reading Duration (s):** Mean = 26.70, Median = 24.87, N = 233
- **Answering Duration (s):** Mean = 30.73, Median = 27.45, N = 233

These metrics offer insights into how participants divide their attention between understanding the question and formulating a response. The aggregated AOI times (presented in the sample table above) further detail specific attentional foci.

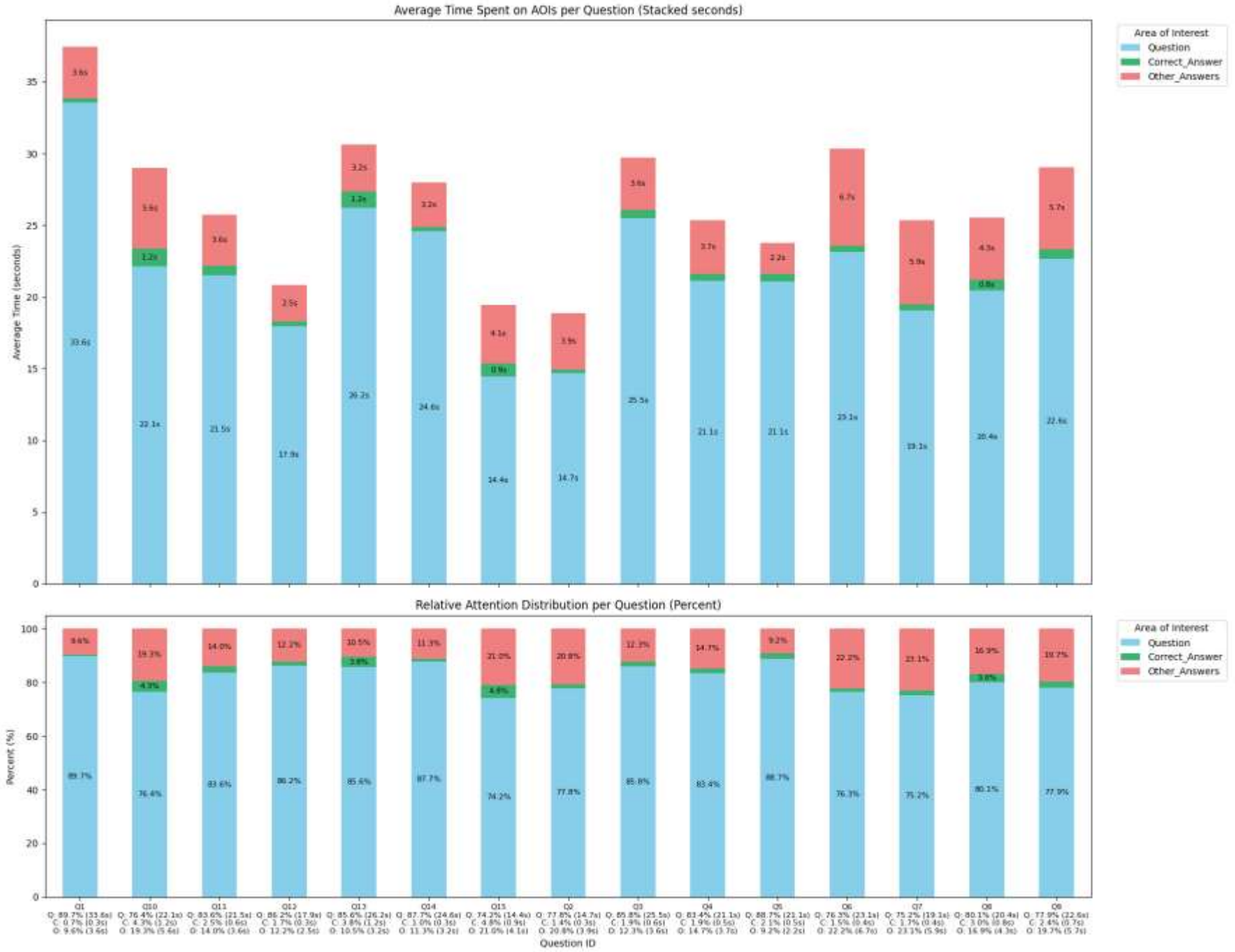
Overall Statistical Summary

This section provides a high-level statistical overview of the entire dataset and the results of the pipeline.

- **Total Participants Analyzed:** 23
- **Total Questions Analyzed:** 15
- **Overall Mean Interaction Time (t_ij):** 57.41 seconds
- **Overall Median Interaction Time (t_ij):** 54.90 seconds
- **Overall Behavioral Label Distribution:**
  - UP: 119 instances
  - NP: 95 instances
  - NA_no_correct: 14 instances
  - INVALID: 5 instances

Visualizations

AOI Time Summary per Question

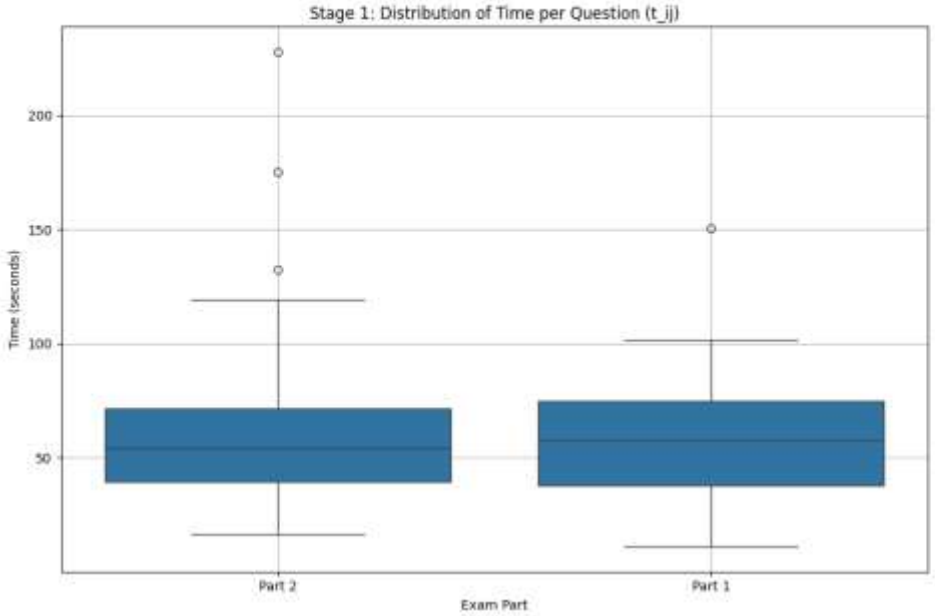

Average Time Spent on AOIs per Question (Stacked seconds)
Average Time (seconds)
Area of Interest
Question
Correct_Answer
Other_Answers
Relative Attention Distribution per Question (Percent)
Percent (%)
Area of Interest
Question
Correct_Answer
Other_Answers
Q1
Q: 89.7% (33.6s)
C: 0.7% (0.3s)
O: 9.6% (3.6s)
Q10
Q: 76.4% (22.1s)
C: 4.3% (1.2s)
O: 19.3% (5.6s)
Q11
Q: 83.6% (21.5s)
C: 2.5% (0.6s)
O: 14.0% (3.6s)
Q12
Q: 86.2% (17.9s)
C: 1.7% (0.3s)
O: 12.2% (2.5s)
Q13
Q: 85.6% (26.2s)
C: 3.8% (1.2s)
O: 10.5% (3.2s)
Q14
Q: 87.7% (24.6s)
C: 1.0% (0.3s)
O: 11.3% (3.2s)
Q15
Q: 74.2% (14.4s)
C: 4.8% (0.9s)
O: 21.0% (4.1s)
Q2
Q: 77.8% (14.7s)
C: 1.4% (0.3s)
O: 20.8% (3.9s)
Q3
Q: 85.8% (25.5s)
C: 1.9% (0.6s)
O: 12.3% (3.6s)
Q4
Q: 83.4% (21.1s)
C: 1.9% (0.5s)
O: 14.7% (3.7s)
Q5
Q: 88.7% (21.1s)
C: 2.1% (0.5s)
O: 9.2% (2.2s)
Q6
Q: 76.3% (23.1s)
C: 1.5% (0.4s)
O: 22.2% (6.7s)
Q7
Q: 75.2% (19.1s)
C: 1.7% (0.4s)
O: 23.1% (5.9s)
Q8
Q: 80.1% (20.4s)
C: 3.0% (0.8s)
O: 16.9% (4.3s)
Q9
Q: 77.9% (22.6s)
C: 2.4% (0.7s)
O: 19.7% (5.7s)
Question ID

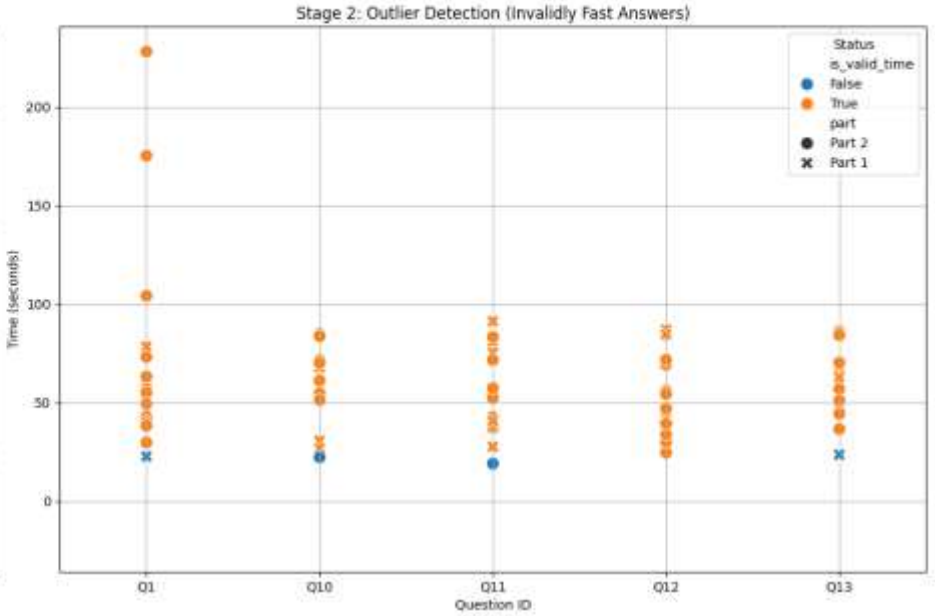
Numeric Summary (per question)

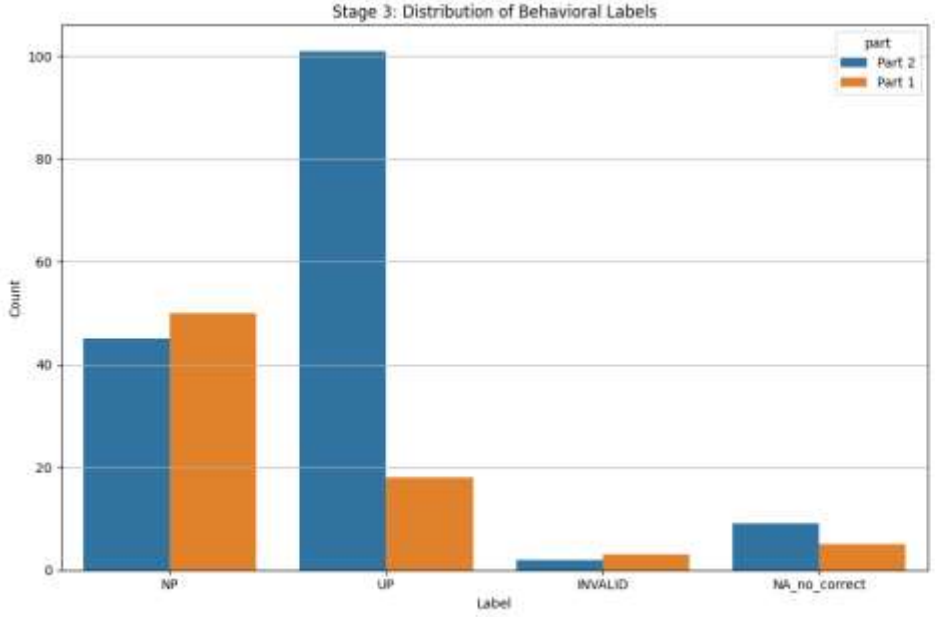
question_id	Question_s	Correct_Answer_s	Other_Answers_s	Question_pct	Correct_Answer_pct	Other_Answers_pct
Q1	33.575	0.252	3.605	89.695	0.673	9.632
Q10	22.147	1.232	5.606	76.408	4.250	19.342
Q11	21.516	0.639	3.597	83.552	2.482	13.966
Q12	17.940	0.345	2.534	86.173	1.655	12.172
Q13	26.204	1.177	3.225	85.618	3.846	10.536
Q14	24.555	0.290	3.161	87.677	1.036	11.288
Q15	14.432	0.928	4.079	74.241	4.776	20.984
Q2	14.683	0.259	3.935	77.783	1.371	20.846
Q3	25.492	0.566	3.644	85.826	1.906	12.268
Q4	21.120	0.479	3.727	83.393	1.891	14.715
Q5	21.091	0.494	2.196	88.689	2.078	9.233
Q6	23.143	0.440	6.737	76.331	1.450	22.219
Q7	19.069	0.421	5.867	75.203	1.660	23.137
Q8	20.445	0.769	4.319	80.071	3.013	16.916
Q9	22.634	0.711	5.719	77.876	2.445	19.679

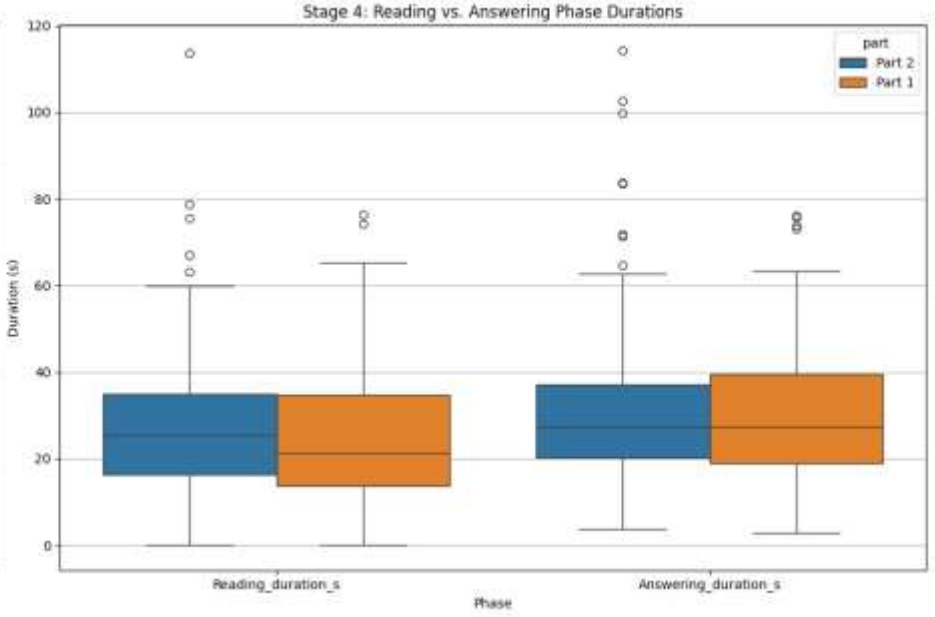
Pipeline Summary Plots

Pipeline Stage Summaries

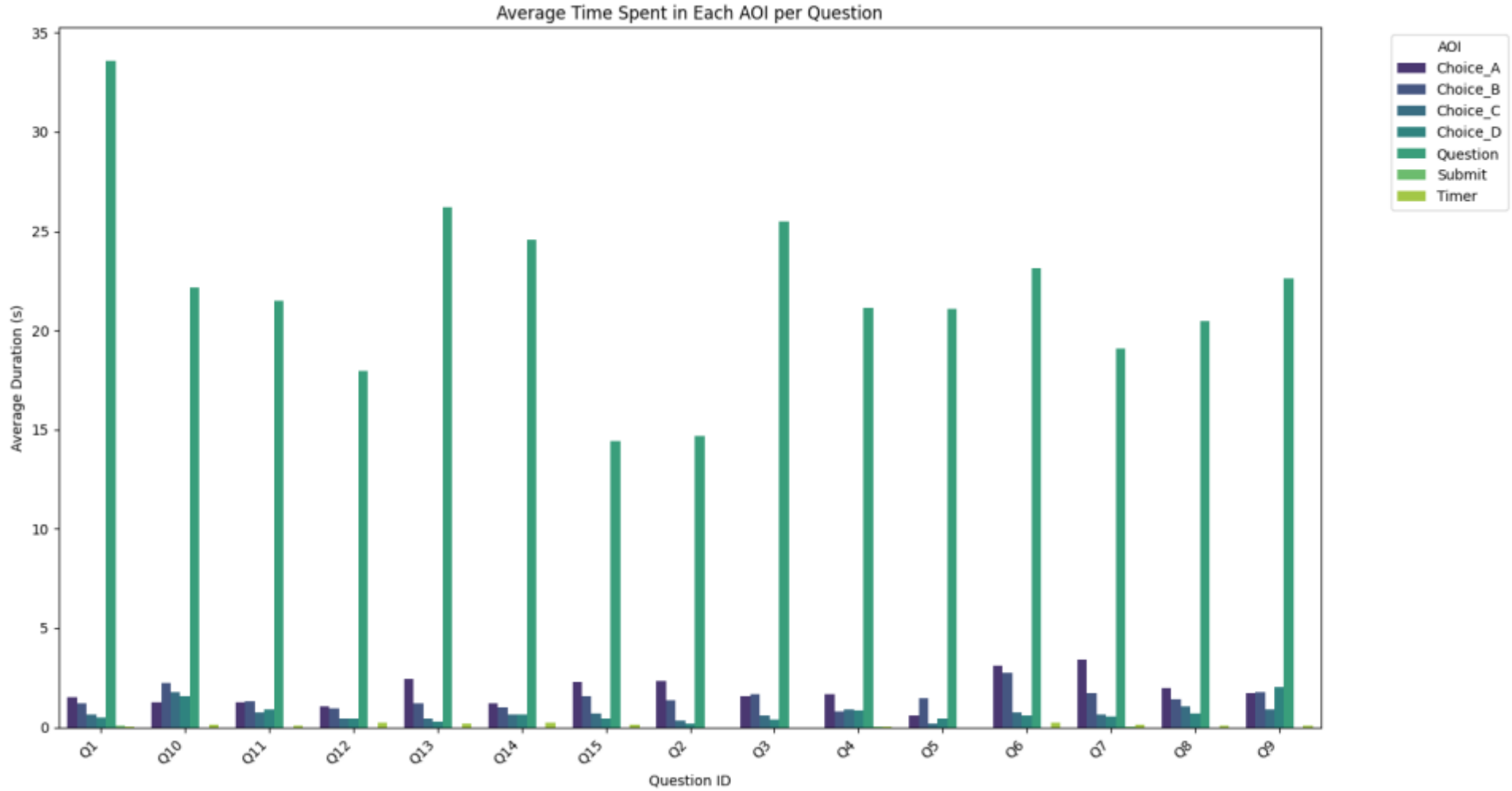




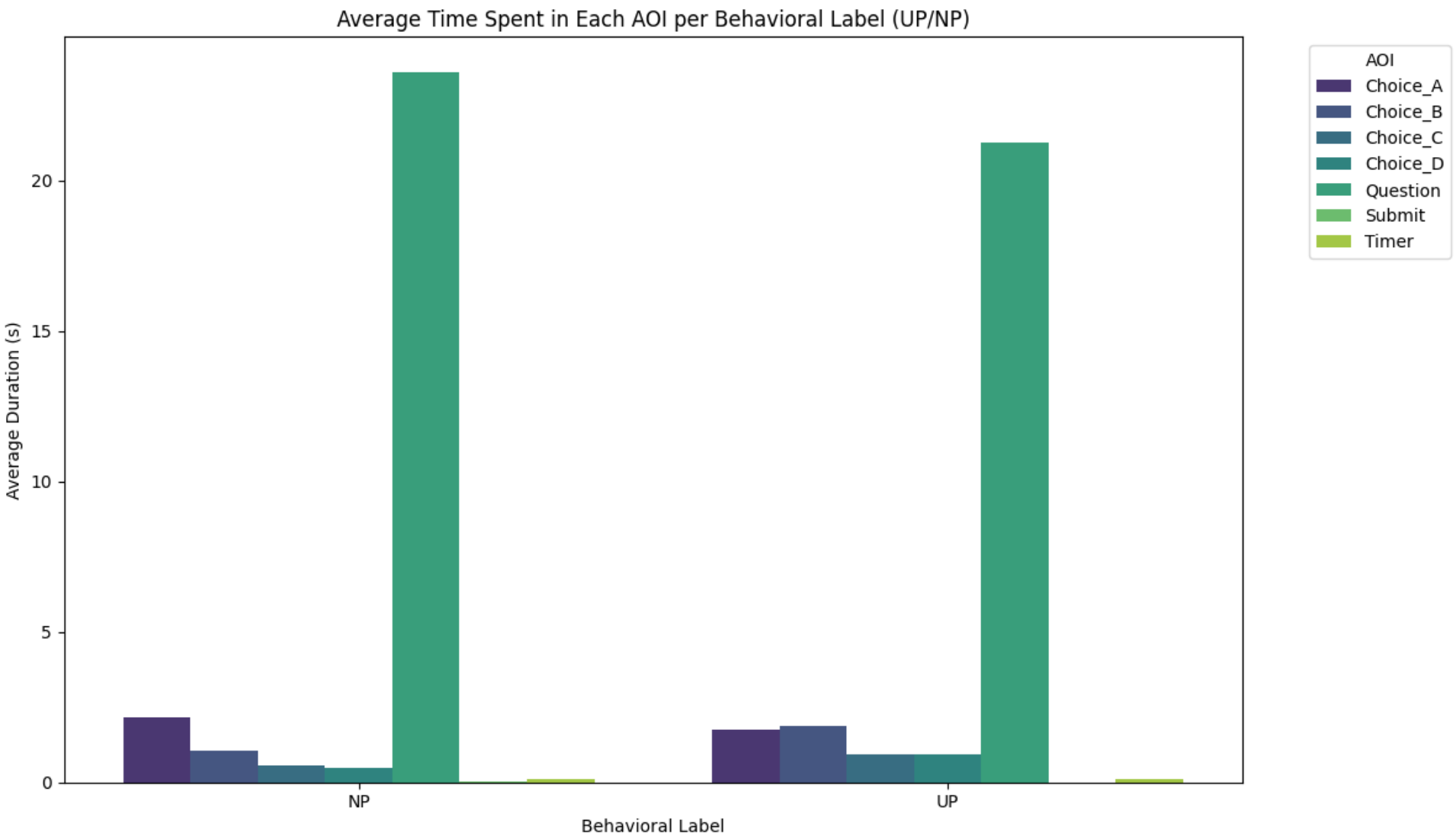




AOI Time per Question



AOI Time per Label



Participant Participant 1