

Ball Pushing Metrics Documentation

This document provides a comprehensive explanation of all metrics computed by the `BallPushingMetrics` class for analyzing fly-ball interaction behavior.

Overview

The Ball Pushing Metrics system analyzes behavioral data from experiments where flies interact with balls in controlled environments. Each metric captures different aspects of the fly's learning and motor behavior during ball manipulation tasks.

Pixel-to-millimeter conversion: All thresholds are given in both pixels and millimeters. The conversion factor is 1 pixel = 0.06 mm (based on 30 mm = 500 pixels).

Core Event Definitions

Basic Event Types

These are metrics that are used as tools to generate the summary metrics.

- **Interaction Event:** A period where the fly is in close proximity to the ball and potentially manipulating it
 - *Close proximity threshold:* ≤ 45 pixels (2.7 mm) distance between fly and ball
- **Significant Event:** An interaction event that results in significant ball displacement
 - *Threshold:* > 5 pixels (0.3 mm) ball displacement
- **First Major Event:** The first significant event that crosses a higher threshold, often considered the "aha moment"
 - *Threshold:* ≥ 20 pixels (1.2 mm) ball displacement
- **Final Event:** The last interaction event that achieves the final distance threshold before task completion
 - *Threshold:* 170 pixels (10.2 mm) for standard experiments, 100 pixels (6.0 mm) for F1 experiments
 - *Note:* This represents the last significant interaction that moves the ball toward the task goal

Temporal Metrics

These metrics capture how behavior changes over time:

Event Counts and Timing

`fly_distance_moved`

Description: Total distance traveled by fly throughout experiment **Calculation:** Sum of frame-to-frame Euclidean distances for fly position **Units:** millimeters

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Calculation: Sum of frame-to-frame Euclidean distances for fly position

Units: millimeters

Interpretation: Overall locomotor activity and exploration behavior

nb_events

Description: Total number of interaction events

Calculation: Count of all detected fly-ball interaction periods, adjusted for experiment duration

Range: 0 to ∞

Interpretation: Higher values indicate more frequent interaction attempts

time_chamber_beginning

Description: Time spent in starting chamber during first 25% of experiment

Calculation: Duration within chamber radius during first quarter of video

Units: seconds

Interpretation: Early chamber attachment behavior; higher values suggest reluctance to explore

persistence_at_end

Description: Fraction of time spent at corridor end (goal area)

Calculation: Proportion of frames where fly is at or beyond corridor end threshold distance

Range: 0.0 to 1.0

Interpretation: Goal-directed persistence; higher values indicate staying near task completion area

interaction_proportion

Description: Fraction of time spent interacting with ball

Calculation: Total interaction duration / experiment duration

Range: 0.0 to 1.0

Interpretation: Task engagement level

nb_significant_events

Description: Number of significant interaction events

Calculation: Count of events where ball displacement exceeds threshold (5 pixels / 0.3 mm)

Range: 0 to `nb_events`

`number_of_pauses / total_pause_duration`

Description: Locomotor pause analysis

Calculation: Count and duration of periods with minimal movement

Units: count / seconds

Interpretation: Behavioral arrest episodes, potentially indicating decision-making

Interpretation: Measures successful manipulation attempts vs. mere contact

`significant_ratio`

Description: Proportion of successful interactions

Calculation: `nb_significant_events / nb_events`

Range: 0.0 to 1.0

Interpretation: Higher values indicate better task efficiency

Key Event Timing

`max_event / max_event_time`

Description: Event/time when maximum ball displacement was achieved

Note: max events are fly specific, each fly has its own peak.

Calculation: Event index and timestamp of the interaction that moved the ball furthest

Units: Index / seconds

Interpretation: Indicates when peak performance was reached

`first_significant_event / first_significant_event_time`

Description: First successful ball manipulation

Calculation: Index and timestamp of first event exceeding displacement threshold

Units: Index / seconds

Interpretation: Learning onset time - how quickly the fly discovers the task

`first_major_event / first_major_event_time`

Description: The "aha moment" - first major breakthrough event

Calculation: Event preceding the first significant displacement above major threshold (≥ 20 pixels / 1.2 mm)

Units: Index / seconds

Interpretation: Moment of behavioral insight or strategy change

final_event / final_event_time

Description: Last significant interaction before task completion

Calculation: Final event achieving distance threshold (170 pixels / 10.2 mm for standard experiments, 100 pixels / 6.0 mm for F1 experiments) before fly exits chamber

Units: Index / seconds

Interpretation: Task completion time and final achievement level

Temporal Dynamics

binned_slope_[0-11]

Description: Ball position slope in 12 time bins

Calculation: Linear regression slope of ball Y-position within each time bin

Units: pixels/second

Interpretation: Captures learning dynamics - how manipulation strategy evolves over time

interaction_rate_bin_[0-11]

Description: Interaction frequency in 12 time bins

Calculation: Number of interaction events per second within each time bin

Units: events/second

Interpretation: Shows activity patterns - when the fly is most/least active

binned_auc_[0-11]

Description: Area under ball position curve in 12 time bins

Calculation: Integral of ball Y-position over time within each bin

Units: pixel-seconds

Interpretation: Cumulative displacement progress over time

Spatial Metrics

These metrics describe the spatial aspects of ball manipulation:

Distance and Displacement

max_distance

Description: Maximum ball displacement from start position

Calculation: Euclidean distance of furthest ball position from initial location

Units: pixels

Interpretation: Peak manipulation achievement

distance_moved

Description: Total distance ball was moved during all interactions

Note: This differs from max_distance as it also counts pulling distances.

Calculation: Sum of Euclidean distances between start/end positions of each event

Units: pixels

Interpretation: Total mechanical work performed

distance_ratio

Description: Efficiency of ball manipulation

Calculation: $\text{distance_moved} / \text{max_distance}$

Range: ≥ 1.0

Interpretation: Values close to 1.0 indicate efficient, directional movement; higher values suggest back-and-forth manipulation

Directional Behavior

pushed / pulled

Description: Count of significant pushing vs. pulling events

Calculation: Events classified by whether ball moves away from or toward fly's starting position, using significant event threshold (5 pixels / 0.3 mm)

Units: count

Interpretation: Reveals manipulation strategy preferences for significant interactions

pulling_ratio

Description: Preference for significant pulling vs. pushing events

Calculation: $\text{pulled} / (\text{pushed} + \text{pulled})$ where both events exceed significant threshold (5 pixels / 0.3 mm)

Range: 0.0 to 1.0

Interpretation: 0.5 = balanced, > 0.5 = pulling more often than pushing, < 0.5 = pushing more often than pulling.

success_direction

Description: Primary successful manipulation direction

Note: This metric is particularly relevant for F1 experiments where the task can be achieved by pulling the ball as well as pushing it.

Values: "push", "pull", "both", or None

Calculation: Direction that achieved threshold displacement (25 pixels / 1.5 mm)

Interpretation: Identifies the fly's successful strategy

Movement and Locomotion Metrics

Velocity Analysis

normalized_velocity

Description: Fly velocity normalized by available space

Calculation: Average velocity divided by ball-start distance

Units: dimensionless

Interpretation: Speed relative to workspace size

velocity_during_interactions

Description: Average fly speed during ball contact

Calculation: Mean velocity during all interaction events

Units: pixels/second

Interpretation: Locomotor activity level during manipulation

velocity_trend

Description: Change in fly velocity over time

Calculation: Linear regression slope of velocity vs. time

Units: pixels/second²

Interpretation: Positive = accelerating, negative = decelerating over session

fly_distance_moved

Description: Total distance traveled by fly throughout experiment

Calculation: Sum of frame-to-frame Euclidean distances for fly position

Units: millimeters

Interpretation: Overall locomotor activity and exploration behavior

Spatial Distribution

chamber_time / chamber_ratio

Description: Time spent in starting chamber area

Calculation: Duration within defined radius of start position / total time

Units: seconds / ratio (0.0-1.0)

Interpretation: Higher values indicate more conservative exploration

time_chamber_beginning

Description: Time spent in starting chamber during first 25% of experiment

Calculation: Duration within chamber radius during first quarter of video

Units: seconds

Interpretation: Early chamber attachment behavior; higher values suggest reluctance to explore

persistence_at_end

Description: Fraction of time spent at corridor end (goal area)

Calculation: Proportion of frames where fly is at or beyond corridor end threshold distance

Range: 0.0 to 1.0

Interpretation: Goal-directed persistence; higher values indicate staying near task completion area

interaction_proportion

Description: Fraction of time spent interacting with ball

Calculation: Total interaction duration / experiment duration

Range: 0.0 to 1.0

Interpretation: Task engagement level

Freeze and Pause Behavior

number_of_pauses / total_pause_duration

Description: Locomotor pause analysis

Calculation: Count and duration of periods with minimal movement, with some time threshold (default: 5 seconds)

Units: count / seconds

Interpretation: Behavioral arrest episodes, potentially indicating decision-making

nb_freeze

Description: Number of freezing events, i.e., short pauses (> 2s)

Calculation: Compute pauses without minimal threshold and keep all pauses >2s.

Units: count

Interpretation: Brief stops, can be fearful events, can be similar to pauses.

median_freeze_duration

Description: Median duration of locomotor pause events

Calculation: Median of all detected pause episode durations

Units: seconds

Interpretation: Typical duration of behavioral arrest periods; longer values may indicate decision-making or fatigue

Learning and Strategy Metrics

Learning Dynamics

learning_slope / learning_slope_r2

Description: Overall learning trend in ball positioning

Calculation: Linear regression of ball Y-position vs. time

Units: pixels/second / R²

Interpretation: Positive slope = successful directional movement; R^2 = consistency

logistic_L / logistic_k / logistic_t0 / logistic_r2

Description: Logistic growth model parameters for ball position

Calculation: Fit of sigmoid function to ball position over time

- **L:** Maximum displacement (plateau)
- **k:** Learning rate (steepness)
- **t0:** Midpoint time (50% achievement)
- **r2:** Model fit quality

Interpretation: Captures S-shaped learning curves typical of skill acquisition

overall_slope / overall_interaction_rate

Description: Global behavioral trends

Calculation: Overall ball displacement rate / total interaction frequency

Units: pixels/second / events/second

Interpretation: Summary measures of performance and activity

auc

Description: Total area under ball position curve

Calculation: Integral of ball Y-position over entire experiment

Units: pixel-seconds

Interpretation: Cumulative manipulation achievement

Strategy and Persistence

interaction_persistence

Description: Average duration of interaction events

Calculation: Mean duration of all interaction episodes

Units: seconds

Interpretation: Longer values indicate sustained manipulation attempts

major_event_first

Description: Whether major breakthrough occurred in first event

Values: True/False

Calculation: Boolean indicating if first_major_event index = 0

Interpretation: Immediate vs. gradual task discovery

Temporal Structure Metrics

Activity Patterns

cumulated_breaks_duration

Description: Total time between interaction events

Calculation: Sum of all inter-event intervals

Units: seconds

Interpretation: Rest/planning time between manipulation attempts

Behavioral Strategy Metrics

These metrics analyze specific behavioral patterns and strategies used by flies during ball manipulation:

Body Orientation

fraction_not_facing_ball

Description: Fraction of time when fly is not facing the ball direction while outside chamber

Calculation: Proportion of frames where fly's body orientation deviates more than 30° from corridor direction (toward ball) when outside starting chamber

Range: 0.0 to 1.0

Interpretation: Higher values indicate distraction or lack of directional focus; lower values suggest goal-directed behavior

Motor Behavior Patterns

flailing

Description: Average motion energy of front legs during interaction events

Calculation: Motion energy computed as sum of squared velocity differences for leg keypoints during ball interactions

Units: dimensionless motion energy

Interpretation: Higher values indicate more energetic leg movement during interactions, potentially reflecting struggle or inefficient manipulation

head_pushing_ratio

Description: Proportion of contacts where head is used for pushing rather than legs

Calculation: Frame-by-frame analysis during contact events to determine whether head or legs are closer to ball

Range: 0.0 to 1.0

Interpretation: 1.0 = pure head pushing strategy, 0.0 = pure leg pushing strategy, 0.5 = mixed strategy

Contact Analysis

median_head_ball_distance

Description: Median distance between fly head and ball during contact events

Calculation: Median Euclidean distance across all contact frames

Units: pixels

Interpretation: Lower values indicate head-pushing behavior; higher values suggest leg-pushing with head maintained at distance

mean_head_ball_distance

Description: Mean distance between fly head and ball during contact events

Calculation: Average Euclidean distance across all contact frames

Units: pixels

Interpretation: Complements median distance; comparison reveals distribution shape of head-ball distances

leg_visibility_ratio

Description: Weighted ratio of front leg visibility during contact events

Calculation: Weighted score based on number of visible front legs per frame during contacts (0-2 legs visible)

Range: 0.0 to 1.0

Interpretation: Higher values indicate better leg tracking quality and potentially more leg-based manipulation

Task Completion Metrics

Achievement Status

has_finished

Description: Binary indicator of task completion

Calculation: 1 if final event exists (ball moved to completion threshold), 0 otherwise

Values: 0 or 1

Interpretation: Simple binary measure of whether fly successfully completed the ball-pushing task

has_major

Description: Binary indicator of major event achievement

Calculation: 1 if a major event was detected, 0 otherwise

Values: 0 or 1

Interpretation: Indicates whether the fly achieved a major breakthrough event during the experiment

has_significant

Description: Binary indicator of significant event achievement

Calculation: 1 if at least one significant event (ball displacement > 5 pixels / 0.3 mm) was detected, 0 otherwise

Values: 0 or 1

Interpretation: Indicates whether the fly achieved any significant ball manipulation event

Experimental Context Metrics

Timing References

exit_time / chamber_exit_time

Description: When fly left experimental chamber

Note: Exit time is also used to compute timing based metrics such as **final_event_time**

Calculation: Timestamp when fly moved beyond chamber radius

Units: seconds

Interpretation: Later exit_time can indicate struggle to exit or lack of motivation to explore.

Threshold Summary

The following table summarizes all thresholds used in the metrics:

Threshold Type	Pixels	Millimeters	Degrees	Used For
Interaction proximity	≤ 45	≤ 2.7 mm	-	Detecting when fly is close enough to ball for interaction events
Significant event	> 5	> 0.3 mm	-	Significant ball displacement; used for significant events, push/pull classification
Major event	≥ 20	≥ 1.2 mm	-	First major breakthrough ("aha moment")
Success direction	≥ 25	≥ 1.5 mm	-	Determining successful manipulation direction (push/pull/both)
Final event (standard)	170	10.2 mm	-	Task completion threshold for standard experiments
Final event (F1)	100	6.0 mm	-	Task completion threshold for F1 experiments (second part)
Body orientation	-	-	30°	Angle deviation from corridor direction for <code>fraction_not_facing_ball</code>

Description: Efficiency of ball manipulation

Calculation: `distance_moved / max_distance`

Range: ≥ 1.0

Interpretation: Values close to 1.0 indicate efficient, directional movement; higher values suggest back-and-forth manipulation

Directional Behavior

`pushed / pulled`

Description: Count of significant pushing vs. pulling events

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Units: count

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has_significant

Description: Binary indicator of significant event achievement

Calculation: 1 if at least one significant event (ball displacement > 5 pixels / 0.3 mm) was detected, 0 otherwise

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