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Descriptive Parameters and Its Hysteresis of the Group Separation and Recombination in Bicycle Points Races: Leader's Velocity and Speed Difference between Leader and Main Group

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Abstract: This study examined the descriptive parameters for separation and recombination processes in a cycling points race. The candidate descriptive parameters were the speed of the leading cyclist and the main group and the difference between their time and speed. We focused on the transition between the four states of peloton configuration (dense state, stretched state, divided state, and escape and dense state) defined by previous studies that occur during the points race. As a result, it was found that the distribution of the leader's velocity and the speed difference significantly differed when the groups were separated and recombined compared to when the state did not change. It was also examined whether the separation and recombination processes had a phenomenon such as a hysteresis depending on the present state. Regarding the leader velocity and the speed difference between the leader and the main group, the state of the group was not uniquely determined by the speed difference, and the influence of the speed difference for separation or recombination depended on the state; that is, there was asymmetry in separation and recombination in a points race. These suggest that the cyclists need the ability to choose an appropriate speed and distance from other cyclists depending on the situation.

Keywords: descriptive parameters; group separation; recombination; bicycle points race; hysteresis

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Citation: Okumura, F.; Yokoyama, K.; Yamamoto, Y. Descriptive Parameters and Its Hysteresis of the Group Separation and Recombination in Bicycle Points Races: Leader's Velocity and Speed Difference between Leader and Main Group. *Appl. Sci.* **2023**, *13*, 1315. https://doi.org/10.3390/app13031315

Academic Editor: Mickey Scheinowitz

Received: 2 January 2023
Revised: 14 January 2023
Accepted: 17 January 2023
Published: 18 January 2023

1. Introduction

In mass-start bicycle racing, because cyclists travel at comparatively high speeds, the aerodynamic drag is a critical factor that influences the outcome of competitions [1]. Therefore, cyclists form dense groups to avoid air resistance. A cyclist running behind another cyclist, called drafting, can reduce air resistance and save energy consumption; however, a cyclist running ahead as a leader receives more air resistance than those behind. Consequently, cooperative behavior, considered altruistic behavior, occurs among cyclists in a self-organizing manner, rotating and taking turns at the front. In contrast, cooperation and self-interested behavior are required to win a competition. A points race held in a cycling velodrome is a competition for accumulated points following the sprint laps held for every specified lap, in this case, every 10th lap. Here, there are several opportunities to receive points; hence, the groups of cyclists constantly switch between cooperative (altruistic) and non-cooperative (self-centered) behaviors and are repeatedly separated and recombined in the race [2].

Many studies on the self-organization of group organisms have been conducted by analyzing groups of insects and animals, such as swarm flocks and herds [3]. These organisms engage in behaviors advantageous for survival by forming groups to reduce energy consumption during movement and their predation probability. Mathematical models have been used to understand the formation of animal groups [4,5]. In contrast, other studies show that animal group collective dynamics are determined in part by an order parameter or collective variable representing the entire group's state and control parameters that influence the state order. To understand these order and control parameters, studies have been conducted to identify animal group dynamics by quantifying the behaviors of individual animals within their collectives. For example, Ballerini et al. [6] studied bird flocks and observed that individual birds exhibited anisotropic tendencies in the direction of their nearest neighbors relative to the motion of the entire flock. Cavagna et al. [7] analyzed the velocity of each individual in large flocks of starlings and found a scale-free behavioral correlation between the average motion and the flock size. Thus, the system of groups has an order parameter or collective variable that represents the entire group's state and control parameters that influence the state order. Trenchard and Perc reviewed collective behavior based on drafting in biological and non-biological systems [8].

Helbing et al. [9] verified a pedestrian crowd simulation that used a social force model with experimental data under various environments, such as bottlenecks and intersections in human crowds. Murakami et al. [10] showed that lane formation was inhibited by the people whose attention was obstructed by the smartphone task and that mutual anticipation affected their self-organization. These studies suggest that variables represent the order of the human groups and are influenced by the control parameters.

Okumura, Yokoyama, and Yamamoto [2] recorded points races that repeated separation and recombination, quantified the configuration of cyclists, and analyzed their state transitions using principal component analysis. The four states, including a dense group, stretched group, a divided group, and an escape group far from a single dense group, were defined in each quadrant on the plane with the first and second principal components. Most state transitions stayed in the same state and transitioned to the adjacent state. However, it is unclear what variables affect the state transition in bicycle racing and how separation and recombination occur.

Trenchard et al. [11] analyzed mass-start bicycle races in the velodrome and identified the phase state of the cycling peloton, which is a group of cyclists, such as the high-density compact phase and low-density stretched phase. Trenchard et al. [12] simulated a peloton applying experimental data in a points race and discussed the importance of cyclists' maximal sustainable outputs (MSO) in terms of power output, the proportion of the current power output to cyclists' MSOs in both the front and drafting positions, and how these factors affect peloton configurations. These factors are the principal control factors that determine peloton configurations. Trenchard [13] refined the description of the stretched phase in terms of the mathematical model described by Trenchard et al. [11,12], that is, as occurring within the term of their PCR (peloton conversion ratio) equation. However, the dynamics of group separation and recombination in cycling races have not yet been analyzed in detail.

Studies of bird flocks have used the function of the velocity of individuals as a variable to represent the population order, such as the polarization of the group's direction [5]. During velodrome cycling competitions, the direction of travel is determined in one direction. Therefore, the velocity of the cyclist running at the head of each group may reasonably be the representing variable of the movement of each group; the velocity of the cyclist who leads the whole and, if there is an escape group, the velocity of the leading cyclist of the main group, which is the largest group, would be the representation of the group state. Additionally, the relative speed difference between the leading cyclist and the leading cyclist in the main group is also considered a promising candidate for a descriptive variable affecting the state transition in the cycling race. Furthermore, the time difference between the escape group and the main group is represented by the group state. In previous research, Trenchard et al. correlated the peloton phase to cyclists' power output [11]. The cyclists' MSO in the leading position and drafting position were determinant variables of phase states and their transitions. However, since MSO is unknown information during the racing competition, and the external power to overcome air resistance is proportional to the cube of speed [14], speed can be used as alternative information for MSO to describe the phase state and transition of bicycle racing. Therefore, we firstly hypothesize that the velocity of the leading cyclist, the velocity of the cyclist in the main group, their speed difference, and the time difference are the candidate descriptive variables for the state transition of groups in the cycling competition, wherein the groups separate and recombine.

Hysteresis often presents in the change in order based on self-organization [15,16]. Hysteresis is the dependence on the state of the system concerning history. In human movement, Kelso [17] found that a phase transition from anti-phase to in-phase occurs in the movement coordination within an individual; however, an in-phase to anti-phase transition could not occur, suggesting hysteresis. Schmidt et al. [18] also showed that hysteresis occurs during the coordination task of leg movements between two individuals sitting on each other, switching between two modes (in-phase and anti-phase synchronization). Aoi et al. [19] verified the hysteresis in the phase transition of gait with four legs by using a robot. In the sports events, Yamamoto and Gohara [20] showed a third-order sequence effect due to hysteresis in the continuously repeated switching of the forehand and backhand tennis strokes. Sørensen, Ingvaldsen, and Whiting [21] also showed that hysteresis occurs in selecting fore-backhand strokes for table tennis. This hysteresis occurs as two discrete processes measured separately from each other. Besides these examples, hysteresis can occur as an asymmetry in one continuous dynamical process, for example, vehicle traffic hysteresis [22].

Trenchard examined hysteresis in a peloton applying the definition in vehicle traffic [23]. He identified three forms of hysteresis using flow analyses based on vehicle traffic research. Specifically, the second of the three was based on the observation of a points race resulting from rapid acceleration followed by periods of decreasing speeds and decreasing the number of cyclists over time. A phenomenon such as hysteresis can be observed in cycling competitions for the state transition; it is believed there is an asymmetry in the separation and recombination of the cycling group and dependence on history as two discrete processes. Okumura, Yokoyama, and Yamamoto [2] quantified the cyclists' global configuration in the points race, including the separated groups, and identified the group states using the principal component analysis results. It is unclear whether hysteresis occurs in the separation–recombining transition in the points race. Therefore, we secondly hypothesize the existence of a phenomenon such as a hysteresis in the separation and recombination of groups in cycling competition.

This study aimed to verify the hypothesis that the descriptive parameters related to the order change of group separation and recombination in the points race are the velocity of the leading cyclist, the velocity of the leader of the main group, the difference between their velocities, and their time difference. The study also verifies the hypothesis of whether group separation and recombination show asymmetric phenomena such as hysteresis.

2. Materials and Methods

2.1. Participants

We analyzed the 201X Japanese National Track Championships men's elite final. The number of participants and average age (mean $\pm$ SD) were 24 and 20.3 $\pm$ 2.1, respectively. The race was held at an indoor velodrome (250 m), and the race's total distance was 30 km (120 laps).

The average speed was 49.3 km/h. The organizer provided verbal informed consent for this study based on written documents, and participants and, if minors, their parents or guardians agreed to be video recorded and analyzed for the research purpose. This study was approved by the ethics committee at the Research Center of Health Physical Fitness and Sports, Nagoya University (28-17), and complied with the Declaration of Helsinki.

2.2. Experimental Setup

We placed a video camera (Sony HDR-PJ450, 30 fps) along with the extension of the centerline of both the main and the back straight and shot the cyclist passing through both center lines. The time during which the front end of the front wheel of all cyclists' bicycles passed the center line was measured, and the time difference after the race leader passed was measured. Measurements were taken every half lap on both the home and the back straight [2].

2.3. Group Definition

According to Olds [14], the drafting coefficient CF_{draft}, which indicates the ratio of air resistance when traveling alone and in drafting, is the function of distance (d_w) between the rear end of the rear wheel of the front vehicle and the front end of the front wheel of the rear bicycle. Moreover, it is derived that the effect of reducing drag by drafting disappears when d_w becomes larger than 3 m. This study defined that the cyclists belong to different groups when d_w is larger than 3 m. d_w was calculated by multiplying the time difference between the two cyclists, the average speed of the subsequent cyclist in a half lap, and a bike wheelbase of 1.6 m. The average speed of the half lap was calculated by the elapsed time of the half lap (125 m). In some cases, small groups occurred in addition to the leading group and the largest group, but in this study, only the leading group and the main group were accounted for.

2.4. Analysis

Trenchard et al. [11] identified dense (compact) and stretched states in bicycle peloton. Okumura, Yokoyama, and Yamamoto [2] defined four states of peloton configuration that emerged during the points races. Each of them is a dense state (DEN; a densely packed state), stretched state (STR; a stretched state of one group), divided state (DIV; the groups are separated), and escape and dense group (ESC; cyclist(s) that escape and are followed by the large, dense pack). In this study, the four states of the peloton at the measurement point every half lap were identified, and the descriptive parameter candidates were verified. Additionally, to analyze descriptive parameter candidates related to state transitions of peloton configuration, this study investigated the measurement points when the state of the peloton changed to different states. We compared the variables when the state did not change, that is, when the state remained the same peloton configuration state, and when the state changed and examined the descriptive variables that affected the state.

2.5. Candidates for Descriptive Parameter

We verified the velocity of the cyclist who passed each lap at the centerline of the home or back stretch (V_{leader}), the velocity of the cyclist in front of the main group (V_{main}), the speed difference between the leader and front of the main group ($\Delta V = V_{leader} - V_{main}$), and the time difference between the leader and front of the main group (ΔT) as the candidate descriptive parameters. Here, the main group is the group with the largest number of cyclists among the groups, defined by d_w mentioned above. We analyzed these parameters in each state and the state transition from STR and DIV.

2.6. Statistics

One-way analysis of variance (ANOVA) was performed to compare parameters in each state, and subsequently, multiple comparisons by Tukey's test were performed. Additionally, in STR and DIV, each parameter, according to the measurement states after half a lap, was tested by Welch's method. Furthermore, multiple comparisons were performed by the Steel–Dwass method, and effect size ($\eta_p{}^2$) was calculated. Multivariate analysis of variance (MANOVA) was performed by Wilks' lambda for V_{leader} and ΔV comparing STR was changed to DIV, and STR remained, and DIV was changed to STR, and DIV remained. Software R (version 4. 2. 0, R development Core Team, Vienna, Austria) was used for statistical calculations [24].

3. Results

3.1. Candidate Descriptive Variables in Each Global State

Figure 1 shows the box plots of V_{leader}, V_{main}, ΔV, and ΔT in each state to compare each descriptive candidate variable in the four global states. The mean and standard deviation of V_{leader} (m/s) in each state were DEN: 13.67 ± 0.73, STR: 14.51 ± 1.28, DIV: 14.43 ± 1.12, and ESC: 13.86 ± 0.71 (Figure 1a). The result of ANOVA show that the effect of the state was statistically significant ($F(3, 236) = 9.239$, $p = 7.84 \times 10^{-6}$, $\eta_p{}^2 = 0.106$). Tukey's multiple comparison test shows that V_{leader} in STR and DIV was significantly higher than V_{leader} in DEN and ESC (STR vs. DEN: $t = 4.200$, $p = 2.199 \times 10^{-4}$, $r^2 = 0.137$, STR vs. ESC: $t = 3.567$, $p = 0.002$, $r^2 = 0.091$, DIV vs. DEN: $t = 3.861$, $p = 8.350 \times 10^{-4}$, $r^2 = 0.120$, DIV vs. ESC: $t = 3.196$, $p = 0.009$, $r^2 = 0.076$).

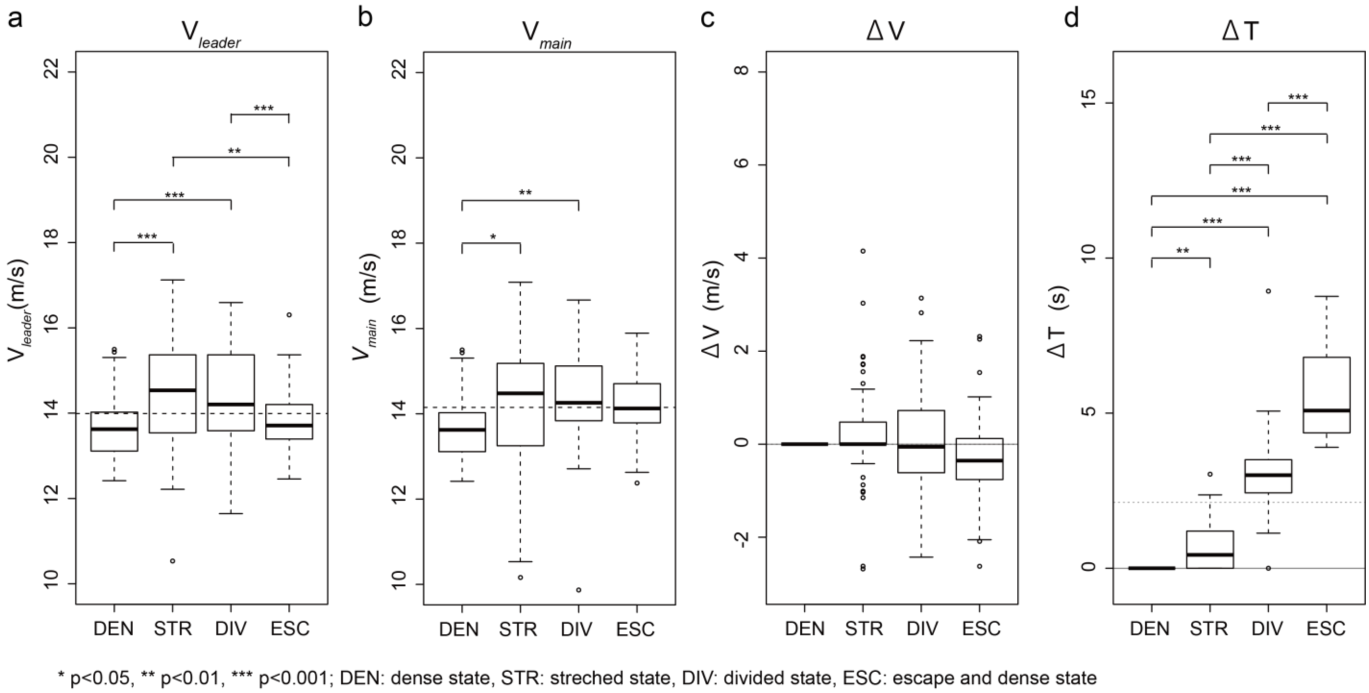

Figure 1. Candidate descriptive parameters for four global states: DEN, STR, DIV, and ESC. The box plots show the comparison of distributions in each parameter: V_{leader} (**a**), V_{main} (**b**), ΔV (**c**), and ΔT (**d**) in each state, respectively.

For V_{main}, the mean and standard deviation in each state were DEN: 13.67 ± 0.73 (m/s), STR: 14.26 ± 1.39 (m/s), DIV: 14.42 ± 1.11 (m/s), and ESC: 14.18 ± 0.78 (m/s) (Figure 1b). The result of ANOVA shows that the effect of the state was significant ($F(3, 236) = 4.478$, $p = 0.004$, $\eta_p{}^2 = 0.054$). The multiple comparisons showed a significant difference between the DEN and STR or DIV, and no other significant differences were observed (DEN vs. STR: $t = 2.828$, $p = 0.025$, $r^2 = 0.067$, DEN vs. DIV: $t = 3.588$, $p = 0.002$, $r^2 = 0.106$).

For ΔV, the mean and standard deviation in each state were DEN: 0 ± 0 (m/s), STR: 0.25 ± 1.00 (m/s), DIV: 0.02 ± 1.00 (m/s), and ESC: −0.32 ± 1.25 (m/s) (Figure 1c). In DEN, because the group was not separated, the value of ΔV was zero (Figure S1). The result of ANOVA showed a significant difference in ΔV among the states ($F(3, 236) = 3.667$, $p = 0.013$, $\eta_p{}^2 = 0.045$); however, no significant differences were observed in the multiple comparison results.

For ΔT, the time difference between the leader and the front of the main group, the mean, and standard deviation in each state were DEN: 0 ± 0 (s), STR: 0.69 ± 0.80 (s), DIV: 3.00 ± 1.15 (s), and ESC: 5.60 ± 1.43 (s) (Figure 1d). The ANOVA result showed a significant difference among the states ($F(3, 236) = 332.1$, $p = 2.00 \times 10^{-16}$, $\eta_p{}^2 = 0.809$). Multiple comparison results showed a significant difference in all combinations (DEN vs. STR: $p = 0.004$, others: $p < 0.001$).

3.2. Group's Separation and Recombination and the Candidate for Descriptive Parameters

To clarify the descriptive parameters of separating a global group in a points race when transitioning from STR to DIV or DEN or staying STR and to clarify the descriptive parameters of the recombination of the global group when recombining from DIV to STR or ESC or staying DIV, Figure 2 shows the box plots of V_{leader}, V_{main}, ΔV, and ΔT when transitioning to each of the defined four states from STR or DIV. Table 1 shows the results of ANOVA using Welch's method and multiple comparisons using the Steel–Dwass method. In this test, the change to DEN from DIV is excluded because the number of samples of the change was small (N = 2). There was no change in ESC for STR. Therefore, when staying in each state and transitioning to the adjacent state, we analyzed the changes in each candidate's parameters.

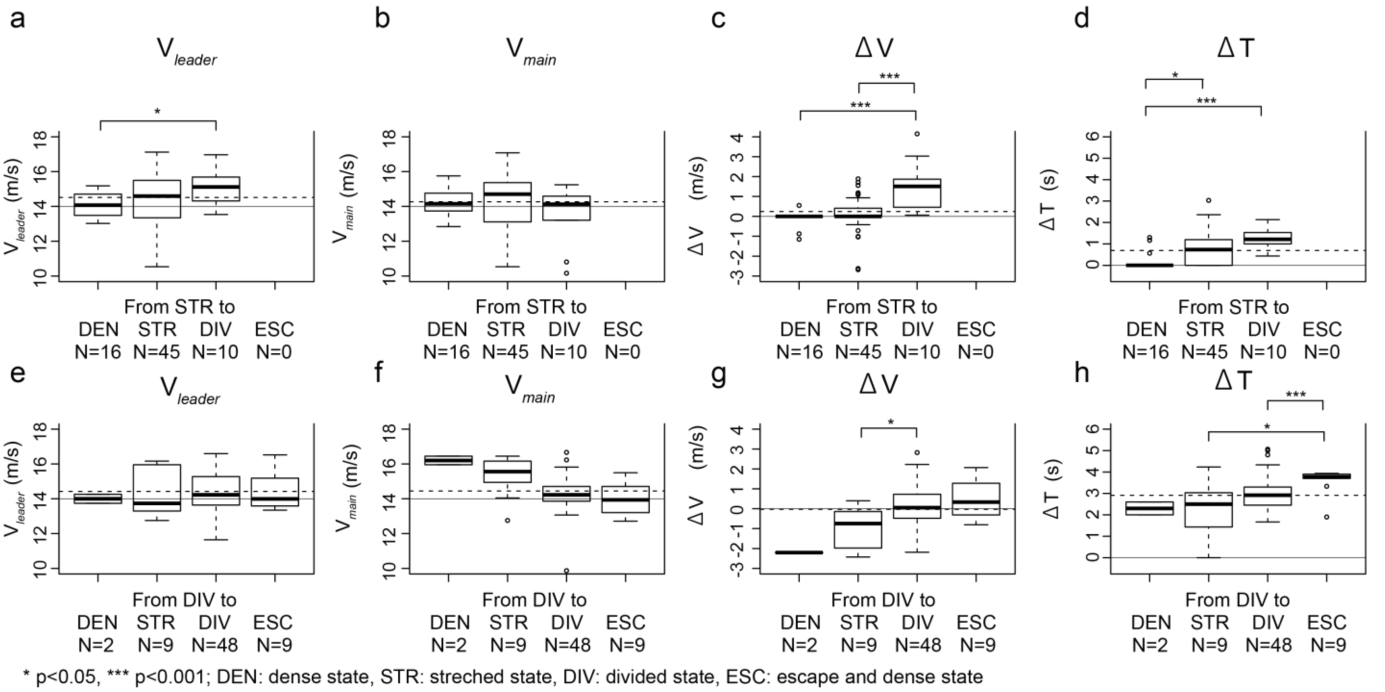

Figure 2. Separation and recombination. The box plots show candidate descriptive parameters V_{leader} (**a**,**e**), V_{main} (**b**,**f**), ΔV (**c**,**g**), and ΔT (**d**,**h**), respectively, when transitioning to each of the defined four states from STR or DIV. The distribution of the variables to each state from STR (**a**–**d**). The distribution of the variables to each state from DIV (**e**–**h**).

Table 1. The results of ANOVA and multiple comparisons for V_{leader}, V_{main}, ΔV, and ΔT.

From	Comparison	V_{Leader}		V_{main}		ΔV		ΔT	
		Welch F Value (df)	Steel–Dwass t Value (df)	Welch F Value (df)	Steel–Dwass t Value	Welch F Value (df)	Steel–Dwass t Value	Welch F Value (df)	Steel–Dwass t Value
Stretched state (STR)	STR→DEN STR→STR	3.644 * (2, 25.1)	1.361 (59)	1.351 (2, 22.1)	-	8.143 ** (2, 21.7)	0.929	14.929 *** (2, 26.3)	2.443
	STR→DEN STR→DIV		2.426 * (24)		-		4.337 ***		3.859 ***
	STR→STR STR→DIV		0.906 (53)		-		4.019 ***		2.223
Divided state (DIV)	DIV→STR DIV→DIV	0.079 (2, 13.7)	- (55)	3.010 (2, 13.8)	-	5.045 * (2, 14.6)	2.560 *	4.829 (2, 14.0)	1.718
	DIV→STR DIV→ESC		- (16)		-		2.252		2.344 *
	DIV→DIV DIV→ESC		- (55)		-		0.810		2.758 *

DEN, dense state; STR, stretched state; DIV, divided state; ESC, escape and dense state; ANOVA, analysis of variance; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

3.3. Separation from the Stretch State

Regarding the transitions from STR, V_{leader} had a significant difference in ANOVA by Welch's method depending on which state transitioned ($F(2, 25.1) = 3.644$, $p = 0.041$, $\eta^2 = 0.049$) (Table 1). In multiple comparisons, there was a significant difference between the change of STR to DEN or DIV ($t = 2.426$, $p = 0.040$, $r^2 = 0.197$); however, there was no significant difference in V_{leader} between staying in STR and when transitioning to different states, that is, STR to STR and STR to DEN or DIV (Figure 2a).

In contrast, V_{main} did not have a significant difference ($F(2, 22.1) = 1.351$, $p = 0.279$, $\eta^2 = 0.055$) (Figure 2b), and ΔV had a significant difference in ANOVA ($F(2, 21.7) = 8.143$, $p = 0.002$, $\eta^2 = 0.298$). In multiple comparisons of ΔV, STR to DIV or DEN and STR to STR or DIV had a significant difference ((STR to DEN vs. STR to DIV) $t = 4.337$, $p = 4.292 \times 10^{-5}$, $r^2 = 0.439$; (STR to STR vs. STR to DIV) $t = 4.019$, $p = 1.724 \times 10^{-4}$, $r^2 = 0.439$) (Figure 2c).

There was a significant difference in ΔT between STR to DEN or STR and STR to DEN or DIV ($F(2, 26.3) = 14.929$, $p = 4.639 \times 10^{-5}$, $\eta^2 = 0.0492$). Multiple comparisons: ((STR to DEN vs. STR to STR) $t = 2.443$, $p = 0.039$, $r^2 = 0.919$; (STR to DEN vs. STR to DIV) $t = 3.859$, $p = 3.350 \times 10^{-4}$, $r^2 = 0.383$) (Figure 2d).

3.4. Recombination of the Group from a Divided State

Regarding the transitions from DIV, the results of ANOVA show that V_{leader} ($F(2, 13.7) = 0.079$, $p = 0.924$, $\eta^2 = 0.003$) (Figure 2e) and V_{main} ($F(2, 13.8) = 3.011$, $p = 0.082$, $\eta^2 = 0.110$) have no significant differences (Figure 2f), and ΔV ($F(2, 14.6) = 5.045$, $p = 0.022$, $\eta^2 = 0.133$) and ΔT ($F(2, 14.0) = 4.829$, $p = 0.025$, $\eta^2 = 0.147$) have significant differences (Table 1). The multiple comparisons show a significant difference between DIV to STR or DIV for ΔV ($t = 2.560$, $p = 0.028$, $r^2 = 0.107$) (Figure 2g).

For ΔT, the ANOVA result shows there was a significant difference in DIV to STR or ESC and DIV to DIV or ESC ((DIV to STR vs. DIV to ESC) $t = 2.344$, $p = 0.050$, $r^2 = 0.256$; (DIV to DIV vs. DIV to ESC) $t = 2.758$, $p = 0.016$, $r^2 = 0.122$) (Figure 2h).

3.5. Effect of Velocity Difference between a Leader and Main Group for Group Separation or Recombination

For further consideration, the relationship between the velocity difference ΔV between the leader and the main group and the state transition, considered to affect the separation and recombination of the group, was analyzed. The horizontal axis is V_{leader}, and the vertical axis is ΔV, and they are plotted separately as the cases of transition from STR to STR and DIV (Figure 3a) and from DIV to STR and DIV (Figure 3b).

When transitioning from STR to DIV compared to when the group stayed in STR (STR to STR), it was distributed in the upper right corner of the area partitioned by $V_{leader} = 14$ m/s, $\Delta V = 0$ (Figure 3a). In contrast, when the group recombines from DIV to STR, it is distributed below the area partitioned by $V_{leader} = 14$ m/s, $\Delta V = 0$ compared to when the group stayed in DIV (Figure 3b). The MANOVA results for V_{leader} and ΔV showed significant differences for STR to STR or DIV (Wilks' $\Lambda = 0.718$ ($F(2, 104) = 9.361$, $p = 1.828 \times 10^{-4}$, $\eta^2 = 0.282$)) and for DIV to DIV or STR (Wilks' $\Lambda = 0.848$ ($F(2, 108) = 4.632$, $p = 0.012$, $\eta^2 = 0.152$)), respectively. In some cases, it remained stretched with a relatively high ΔV of 2.0 m/s (Figure 3a). In this situation, the group was on the verge of separating and might transition to a divided state at the next measurement point. Even in the stretched peloton configuration state, the group defined as "group definition" was formed. Therefore, even if the distance between the leading group and the main group widened due to the large ΔV, it might remain in a stretched state with the presence of a small chasing group in front of the main group.

This suggests that the combination of V_{leader} and ΔV was regarded as the descriptive parameter for state transition between STR to DIV and DIV to STR; however, each V_{leader} and ΔV was not considered as the descriptive parameter independently.

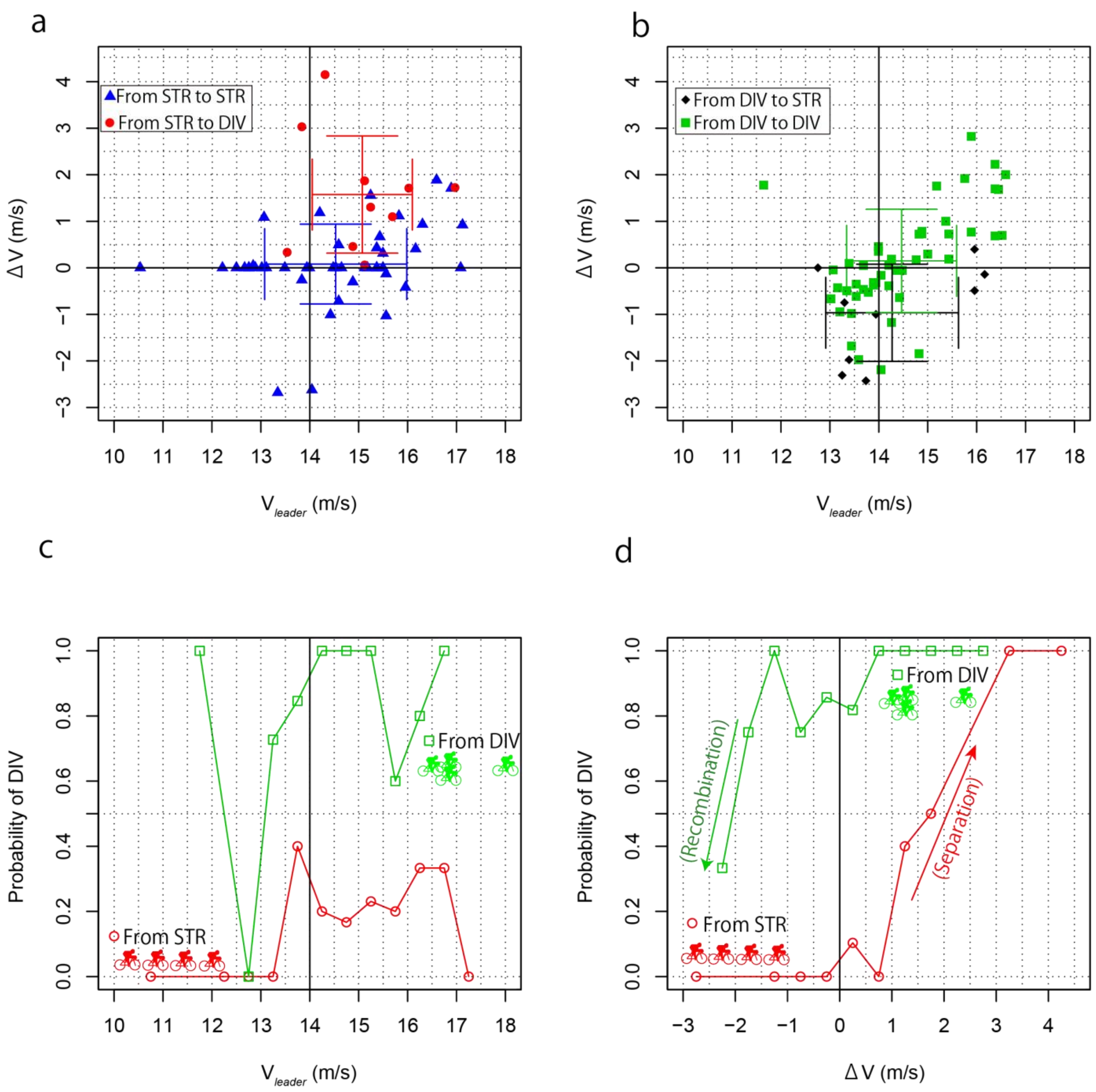

Figure 3. The relationship between V_{leader} and ΔV in the transition from STR and DIV. (**a**) V_{leader} and ΔV when staying STR (blue) and transitioning from STR to DIV (red). (**b**) V_{leader} and ΔV when staying DIV (green) and transitioning from DIV to STR (black). A crossing point of the error bar shows the mean value, and the width of the error bar shows the standard deviation. The median of V_{leader} is 14 m/s. (**c**) The probability of DIV for V_{leader} when transitioning from STR (red) and DIV (green). For V_{leader}, in the grid with 0.5 m/s in (**a**) and (**b**), the probability of transitioning to a divided state was calculated. (**d**) The probability of DIV for ΔV when transitioning from STR (red) to DIV (green). For ΔV, in the grid of 0.5 m/s in (**a**) and (**b**), the probability of transitioning to a divided state was calculated.

3.6. Hysteresis in Separation and Recombination in the Points Race

To verify the hypothesis that asymmetry such as hysteresis may occur in the separation or recombination of the group in a points race, this study examined the speed of the leader and the speed difference between the leader and the main group during the separation (transition from STR to DIV) and the recombination (from DIV to STR). Figure 3c,d show the probability from the current state "to DIV" for V_{leader} and ΔV, respectively. Figure 3c shows that even if the same V_{leader} is 14 m/s, the probability of "to DIV" is different between the separation and recombination, that is, from STR to DIV and from DIV to STR, respectively. Moreover, Figure 3d shows a similar hysteresis; for example, the probability of "to DIV" is different between STR to DIV and DIV to STR at ΔV = 1.75 m/s.

This suggests that the process of separation and recombination cannot be determined solely by V_{leader} and ΔV but depends on the current state of the group.

4. Discussion

This study examined the descriptive parameter related to the global state transition of group separation and recombination and the hysteresis concerning the global state transitions.

In the candidate descriptive parameters analysis in each global state, including the stretched and divided state, the speed of the leading cyclist (V_{leader}) was higher than in other states (Figure 1a). The speed of a leading cyclist may be too high for the follower to sustain when approaching maximal sustainable output when the group stretches or separates. According to Trenchard et al. [11], group separation in a cycling race occurs when a drafting or following cyclist cannot sustain the pace of the leading rider even by drafting. Therefore, group stretch and separation are a consequence of increases in competition speeds that approach cyclists' maximal sustainable outputs. The time differences between the leader and the front of the main group (ΔT) became larger following the state transition from dense to stretched, divided, and escape and dense state. This suggests that time difference could be regarded as an order parameter corresponding to the global state transition defined by Okumura, Yokoyama, and Yamamoto [2].

When focusing on the separation and recombination, there was a significant speed difference between the speed of the leading cyclist and the velocity of the front of the main group (ΔV); that is, there was a significant difference between the case where the state was maintained and the case where the group was separated from a stretched to divided state, or the group was recombined from a divided to stretched state (Figure 2c,g). However, the speed of the leading cyclist did not significantly differ between the separation and recombination (Figure 2a,e). The time difference between the speed of the leading cyclist and the velocity of the front of the main group was considered to have a relative relationship between the speed of the leader and the main group.

To examine the relationship between the speed of the leader and the main group, this study analyzed the speed of the leader and the speed difference between the leader and the main group when the group separated, the stretched group was maintained, the group rejoined, and the divided state was maintained. When the group was separated, the leader's velocity tended to be higher, and the speed difference was positive; that is, the leader tended to be faster than the main group compared to when the group remained stretched and was not divided. This suggests that for the group to be separated, it is necessary to make a difference in velocity and increase the velocity. When speeds are low relative to cyclists' maximal speed capabilities, it is challenging for cyclists to "attack" and escape from the group because chasing cyclists have abundant energy to chase the attacker and to reduce any separations generated by the attacking cyclist. Accelerating to 14 m/s or more and escaping from the group requires a further speed difference of 1.0 m/s or more; that is, to escape from a pack, an attacking cyclist needs to attain speeds at least 1.0 m/s more than the followers. However, our observation was of an elite-level men's velodrome race; hence, this may be applicable only to narrow circumstances. Trenchard [13] introduced a random acceleration parameter (RAP) in the range of 0.0–2.0 m/s to the simulation of a cycling competition. RAP is a random acceleration added to the velocity of each agent, which was incorporated into a general algorithm based on a simulation of a flock of birds [11] to better reproduce a cycling competition. In Trenchard's simulation, RAP simulated cyclists' adjustments in speed to generate passing between cyclists at comparatively low speeds, but RAP was not high enough to cause separations in the peloton. This suggests that the leader's velocity and the speed difference between the leader and the main group were critically important to descriptive parameters for the separation and the recombination, partially supporting the first hypothesis.

Regarding the second hypothesis, we could find hysteresis in the separation and recombination state transitions. Trenchard did not account for group divisions for analysis of peloton hysteresis [22]; however, our observation supports his observation. For instance, there was a rapid acceleration at about lap 9.5 up to lap 10, in which the peloton achieves a stretched state; this is followed by a gradual deceleration from laps 10 to 13, and all the while, the peloton remains in the stretched state (Supporting Figure S1). This confirms the hysteresis identified by Trenchard involving asymmetric acceleration and deceleration epochs [22]. The group separation was caused by the acceleration of the leading cyclist and the resulting increase in the speed difference from the main group, and the recombination of the groups was caused by the pursuit of the main group at speed faster than the leader. However, even though these variables were the same value, the separation and recombination of groups did not always occur (Supporting Figure S1); that is, the state of the group was not uniquely determined by the speed difference between the leader and the main group, and the influence of the speed difference for separation or recombination depended on the group state at that time. This suggests that the group separation and recombination in a points race occur by different mechanisms. There are differences in cyclists' conditions between a lap near the beginning of the race when cyclists are fresh and a lap halfway through the race when the cyclists may be starting to fatigue. This factor can affect hysteresis. For example, the transition from stretched state to divided state in LAP18.5 occurred in half a lap due to the velocity difference (>0) between the leader and the main group. In contrast, in the recombination in LAP60, the interval between the groups was shortened due to the speed difference (<0) between the leader and the main group; the interval between the groups was so vast that the divided state continued for one lap, and subsequently, the transition to the stretched state occurred (Supporting Figure S2). This was related to the sprint lap of earning points, and the transition of the state of the group occurred depending on the group state at that time, and the group state is a combination of self-organized dynamics and top-down constraints due to competition rules [25].

5. Conclusions

The group separation results from self-interested behavior in an attempt to score points in the second half of the tenth lap. The group recombination results from the termination of selfish non-cooperative behavior after earning points and the resumption of altruistic, cooperative behavior in the first half of ten laps. Considering conserving energy consumption, it is not necessary for the leader to have an extended time gap with the main group, and the large main group behind would also be recovering while conserving energy consumption. This suggests that the time gap required to sustain group separation is dependent upon relative fatigue between leading and following riders. To manage such time differences, cyclists must develop tactical skills and sufficient fitness to optimize their energy expenditures throughout a range of rapidly changing competitive circumstances. These suggest that the cyclists need the ability to choose an appropriate speed and distance from other cyclists depending on the situation, for example, remaining distance, remaining laps for the sprints, or the critical moment for success or not.

Since this study analyzed only one points race, future research needs to include the analysis of additional races in order to confirm our results. The accuracy of measuring speed is also one of the limitations of our study. We calculated the speed based on the time it took to complete the 125 m half lap. However, as the cyclist moves left and right and climbs the bank, the distance traveled changes. For more precise speed measurement, an instrument such as a speedometer should be used to measure. Furthermore, because cyclists are required to make instantaneous judgments, new methods for collecting all movements in such races need to be developed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13031315/s1, Figure S1: The time series of parameters. Figure S2: The Asymmetry between separation and recombination of groups.

Author Contributions: Conceptualization, F.O. and Y.Y.; methodology, F.O. and Y.Y.; software, F.O.; investigation, F.O. and Y.Y.; resources, Y.Y.; data curation, F.O.; writing—original draft preparation, F.O.; writing—review and editing, K.Y. and Y.Y.; visualization, F.O. and K.Y.; supervision, Y.Y.; project administration, Y.Y.; funding acquisition, K.Y. and Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Japan Society for the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (KAKENHI, Grant Number 19KK0283, 20H00572).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Research Center of Health Physical Fitness and Sports, Nagoya University (28-17).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Japan Cycling Federation (JCF) for their support of this study.

Conflicts of Interest: The authors declare no conflict of interest.

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