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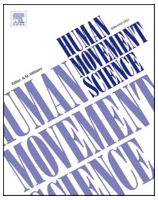

Affordance-based control of braking in cycling: Experience reveals differences in the style of control

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ABSTRACT

We investigated whether in an in-situ collision avoidance experiment cyclists regulate braking by adopting an affordance-based control strategy. Within an affordance-based control strategy for braking, deceleration is controlled relative to the maximum achievable deceleration rather than by nulling out deviations from ideal deceleration, and potentially allowing for different braking styles. Twenty active- and eighteen inactive-cyclists were asked to cycle on a straight path in an indoor gym and to stop as close as possible in front of a stationary obstacle. Maximum achievable deceleration was manipulated by loading the bike: no-load, load-5 kg, and load-10 kg. Two approach distances were used to vary cycling speed. Participants in both groups stopped farther from the obstacle when approaching with long- than short-initial distance conditions. No systematic effects of loading on braking performance and control were found across the two groups. However, both groups did increase the magnitude of brake adjustments as ideal deceleration increased and got closer to the action boundary, even when current deceleration approached the ideal deceleration. This indicates that participants adopted an affordance-based control strategy for braking. Two braking styles were identified: an aggressive style, characterized by a late braking onset and a high, steep peak in ideal deceleration, and a conservative style, characterized by an early braking onset and gradual, linear increase in ideal deceleration. The aggressive braking style was more prevalent among the active-cyclists. We suggest that the braking styles emerge from differences in calibration between information and action. The novelty of our work lies in confirming that cyclists adopt an affordance-based control strategy in an in-situ experiment and in demonstrating and explicating how affordance-based control can incorporate the emergence of different styles of braking.

1. Introduction

The proposal that perceived affordances underpin movement control has gained increasing attention in empirical studies grounded

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within the ecological approach to perception and action (Blau & Wagman, 2022; Dicks, Davids, & Button, 2010; Fajen, 2005a, 2005c, 2007; Postma, Lemmink, & Zaal, 2018; Postma, Smith, Pepping, Van Andel, & Zaal, 2017; Smith & Pepping, 2010; van Andel, Cole, & Pepping, 2017; van der Kamp, Dicks, Navia, & Noël, 2018; van Hof, van der Kamp, & Savelsbergh, 2008; Warren, 1984; Withagen & Michaels, 2005; Zheng, de Reus, & van der Kamp, 2021; Zheng, van der Kamp, Song, & Savelsbergh, 2022). Affordances are the possibilities for action that emerge within the relationship between an actor and its immediate surroundings (Gibson, 1979; Stoffregen, 2000; Warren, 1984). For instance, when approaching an obstacle, a cyclist must perceive whether it is (still) possible to decelerate and stop in time. They will stop safely if they control braking such that the perception of stop-ability is sustained, underlining that the perception of affordances is grounded in the individual's action capabilities. In braking, this refers to the capability to decelerate sufficiently strong to bring a car or bike to a stop (Fajen, 2005b, 2007). These capabilities for braking are not only determined by individual constraints (e.g., muscle power and fatigue, body weight, mood), but also by vehicle (e.g., the gain of the brakes, vehicle weight, load) and environmental constraints (e.g., weather conditions, slipperiness of the road) (Skrucany, Vrabel, & Kazimir, 2020; van Andel et al., 2017). When braking capabilities are reduced, for instance when carrying an additional load on a bike, more time is needed to stop with the same braking strength, and the cyclist must initiate braking earlier and/or brake more firmly. However, if maximum braking capability is insufficient to achieve the required deceleration, then safe stopping is no longer possible. The perception of the affordance of stop-ability cannot be maintained any longer and the cyclist may opt to swerve out to avoid the obstacle (or brace for impact).

Researchers within the ecological approach have examined what and how information controls an unfolding action. This information-based control describes the lawful relation between information and movement (Andersen, Cisneros, Atchley, & Saidpour, 1999; Lee, 1976; Michaels & Oudejans, 1992; Savelsbergh, Whiting, & Bootsma, 1991; van der Kamp, Bennett, Savelsbergh, & Davids, 1999), including the (visual) control of braking, especially evoking error-nulling control strategies (e.g., tau-dot model [Lee, 1976; Yilmaz & Warren, 1995], constant deceleration model [Andersen et al., 1999]). For example, Lee (1976) mathematically demonstrated that the optical variable *tau*, defined as the inverse of the rate of change of the optical angle as the observer approaches a stationary obstacle (Lee, 1976), directly specifies the (momentary) remaining time until collision (i.e., time-to-contact) (for a more detailed description, see Appendix A). In fact, Lee proposed the constant *tau-dot* strategy, which holds that the ideal rate of deceleration to avoid a collision (i.e., the rate of deceleration that will bring the observer to a stop at the intended location without any additional braking adjustments needed) is achieved by holding the rate of change of *tau*, namely *tau-dot*, constant at the margin value of -0.5. Hence, when *tau-dot* is -0.5 the vehicle will stop in time, while when *tau-dot* deviates from this margin, adjustments in braking are required to cancel-out or 'null' the deviation. In this case, drivers must increase deceleration when *tau-dot* is smaller than -0.5 and decrease deceleration when *tau-dot* is larger than -0.5. Indeed, braking patterns that are consistent with the constant *tau-dot* strategy have been observed in virtual environments (Andersen et al., 1999; Rogers, Kadar, & Costall, 2005; Van Der Meer, Svantesson, & Van Der Weel, 2013; Yilmaz & Warren, 1995), but also in-situ braking for car driving (Rock, Harris, & Yates, 2006) and bicycling (Rodrigues, Bertoloni, Ferracioli, & Tani, 2006; Rodrigues, Schiavon, & Macegoza, 2012). Rodrigues et al. (2006) asked cyclists to accelerate a bicycle until they entered a zone at 14 m from an obstacle, in which they were free to start braking to avoid collision with an obstacle. Participants performed the task within three self-propelled velocity conditions (high, medium, and low) and the results demonstrated that participants accomplished the task by holding *tau-dot* constant at -0.54, -0.54, and $-$ 0.55 in the three velocity conditions, respectively. Rodrigues et al. (2012) also found that with curvilinear trajectories tau-dot was significantly unaltered and held at approximately -0.5, irrespective of velocity. These results provide strong support for cyclists using the constant *tau-dot* strategy for braking regulation. Yet, although empirically robust, Fajen (2005, 2007b) argued that information-based control is limited in explicating how actors control their actions (see also Harrison, Turvey, & Frank, 2016). Principally, it does not inform whether the actor can successfully achieve the task requirements. For example, the *tau-dot* specifies what needs to be done (i.e., increase or decrease deceleration), but not if it can be done (Fajen, 2005b, 2007). This means that if the rate of deceleration needed for successful braking exceeds the maximal achievable deceleration, then it would be impossible to stop in time, but this cannot be known by an actor using a tau-dot strategy. Because in the *tau-dot* strategy the use of information is not scaled to action, this strategy (like other error-nulling strategies) remains mute on whether it is possible to stop in time.

Consequently, Fajen (Fajen, 2005a, 2005b, 2005c, 2007) proposed the affordance-based control strategy. This strategy holds that information that controls action is scaled to the actor's capabilities, that is, to what an actor can maximally achieve, or their action boundaries. In braking, for example, the maximum achievable deceleration defines the boundary that separates the action of stopping safely from possible to impossible. To safely stop, the drivers must make brake adjustments so that the required deceleration does not exceed the maximum achievable deceleration (Fajen, 2005a, 2005c, 2007, 2008). In other words, the driver must brake in such a way that the perception of stop-ability is sustained. Therefore, the perceived required deceleration is specified in units of maximum deceleration (Fajen, 2007). In fact, braking adjustments are only (or especially) needed if the required or ideal deceleration threatens to get close or exceed the maximum achievable deceleration, rather than when it diverges from the current deceleration as per error-nulling strategy (Fajen, 2005a, 2007) (See Appendix B for a more detailed description). To test both affordance-based control and error-nulling strategies, Fajen had drivers stopping a vehicle at a stop sign in a series of experiments in a simulated environment (Fajen, 2005a, 2005c, 2007, 2008). Participants controlled car braking by pulling a joystick from the center position, so that deceleration proportionally increased the further the joystick was pulled away from the center position (Fajen, 2005a, 2005c). Fajen (2005c) manipulated drivers' braking capabilities by varying the strength of the brake across groups. That is, the same amount of joystick displacement resulted in different decelerations, creating a weak-brake (maximum deceleration of 5 m/s^2), a medium-brake (maximum deceleration of 7 m/s^2), and a strong-brake group (maximum deceleration of 9 m/s^2). Fajen (2005c) reasoned that changes in action control following manipulation in action capabilities can only be explained by affordance-based control, and not by the error-nulling models. He reported that the mean ideal deceleration at braking onset was lower for the weak-brake group (i.e., they started adjusting earlier) compared to the medium-brake and strong-brake groups. However, when plotting the ideal deceleration (i.e., the constant deceleration required to exactly stop at an obstacle) at braking onset in units of maximum deceleration (i.e., % of Dmax), group differences were absent, indicating that control was indeed scaled to action capability (Fajen, 2005c). Additionally, Fajen (2005a) analyzed the occurrence of brake adjustments for intervals when the difference between current and ideal deceleration was close to zero (i.e., between – 1.0 and 1.0 m/s^2). In these intervals, which have *tau-dot* values of approximately −0.5, a *tau-dot* strategy would not expect any brake adjustments, because errors are already nulled. However, drivers were observed to still make brake adjustments and were more likely to increase brake pressure when the ideal deceleration got closer to the maximum deceleration (i.e., ~90% of the brake adjustments resulted in increases in deceleration) than when ideal deceleration was close to zero (Fajen, 2005a). This indicates that brake adjustments were made to ensure that ideal deceleration did not exceed the maximum achievable deceleration, also when there was no difference between current and ideal deceleration (Fajen, 2005a). Fajen concluded that drivers take into account their action capabilities and, therefore, control their action based on perceived affordances (Fajen, 2005a, 2005c, 2007, 2008).

Perhaps somewhat paradoxically, the empirical studies on the affordance-based control of braking have all been conducted in virtual environments (Fajen, 2005a, 2005c, 2007, 2008). From the perspective of ecological psychology, from which the concept of affordance originates (Gibson, 1979), a virtual environment is potentially insufficiently representative for the dynamical and reciprocal actor-environment relation defining everyday actions. For instance, there are no physical consequences of collision in a virtual environment, which may affect when drivers start making brake adjustments when approaching their action boundaries. And although optical information in virtual environments nowadays has high fidelity, non-optical information associated with inertia is missing. This may be especially critical for calibrating (i.e., adapting to internal or external changes) when action capabilities change. Hence, we aimed to test Fajen's affordance-based control of braking in an in-situ braking experiment, and specifically examined if cyclists with different levels of experience take their action capabilities into account when braking to stop at an obstacle (Fajen, 2005a, 2005c, 2007, 2008). In the present study, we manipulated the action capabilities, as defined across the person-bicycle system, by adding, unknown to the participants, additional load to the bike. We sought evidence whether adaptative brake adjustments would be made relative to maximum achievable decelerations or to nulling differences with ideal deceleration. In addition, we also addressed possibly different styles of braking. For example, on a relaxed weekend trip cyclists may opt to brake early and very gradually, while when in a rush they may start braking late and very forcefully. The affordance-based control approach potentially allows for accommodating of these intra- and inter-individual variations in the control of braking. Fajen (2005b) wrote, *"In braking, for example, one could adopt a conservative style and minimize collisions by making adjustments to keep the ideal deceleration near the bottom of the safe region, close to zero. Or one could adopt a more aggressive style to minimize approach time by allowing the ideal deceleration to draw near the top of the safe region, close to maximum deceleration"* (p. 726). The safe region here represents the field of solutions within the action boundaries, that is, between zero or minimum and maximum deceleration. All trajectories within these action boundaries are adequate for safe stopping (Fajen, 2005b). That means, although actors use the same general control strategy (i.e., keeping the ideal deceleration below maximum deceleration), they can still show different styles of control based on individual or contextual specific requirements (e.g., mood, likelihood of being fined etc.). In this respect, in in-situ braking, a relatively conservative style of braking may be expected due to a real risk of physical damage following a collision compared to virtual braking. The differences in style may also relate to skill or experience. That is, experienced individuals have been shown to have greater sensitivity to their action boundaries (Dicks et al., 2010; Higuchi et al., 2011; Seifert, Dicks, Wittmann, & Wolf, 2021), which would allow them to explore different styles of control. For example, Zheng et al. (2021), (see also Dicks et al., 2010) showed that both less and high skilled football goalkeepers took their action capabilities (i.e., the minimum time they needed to reach the ball) into account when trying to stop a penalty kick, but high skilled goalkeepers acted closer to their action boundary (Zheng et al., 2021). Analogously, skill level or degree of experience may also shape the chosen braking trajectories within the safe region, resulting in different styles of braking.

The main objective of this study was to investigate whether the control of braking of cyclists in in-situ environments is affordance-based. We assessed this through the utilization of two distinct methods. First, we aimed to manipulate braking capabilities by adding loads to the bicycle, with the heaviest load reducing maximum deceleration the most and consequently increasing the time required to stop. We anticipated lower Dideal at braking onset (i.e., earlier braking onset) in the +10 kg condition compared to the +5 kg and no-load conditions. However, when subsequently expressing Dideal at braking onset in units of maximum deceleration (i.e., % of obsDmax), load-related differences would disappear, corroborating Fajen's findings (2005c). Second, we aimed to examine if brake adjustments still occurred when current and ideal deceleration were zero or close to zero (i.e., when deceleration error is already nulled). If participants use an error-nulling strategy, no further brake adjustments are expected (Lee, 1976). By contrast, if participants use affordance-based control, brake adjustments may still occur and would increase in magnitude as ideal deceleration increases and gets closer to the action boundary (Fajen, 2005). As a secondary objective, we explored if level of experience influences the style of braking. We expected that active-cyclists would feel safer or more in control and thus be more likely to adopt an aggressive style of braking, performing closer to their maximum action capabilities, compared to inactive-cyclists.

2. Method

2.1. Participants

An a priori power analysis (G*Power 3.1.9.7) for a repeated measures analysis of variance (RM-ANOVA) indicated a minimum sample size of thirty-six subjects (i.e., $\beta = 0.80$, $\alpha = 0.05$, effect size $f = 0.20$). Forty adults (16 females) who voluntarily participated in this study were recruited from the city of Bauru, Brazil. Before the study, they had completed a questionnaire designed to estimate cycling experience (Q1 - How old were you when you learned to ride a bike?; Q2 – How many days a week do you typically cycle in the city?; Q3 – How many kilometers do you typically cycle per day?) and physical fitness level (Q1 – Do you practice any aerobic physical activities, except cycling?; Q2 – How often do you practice it weekly?) within the six months preceding the experiment. Participants were eligible to take part in the study as *active-cyclists* ($n = 20$) if they reported experience in urban cycling (i.e., using a bicycle as a way of commuting through the city) at least three times a week, with weekly and annually distances of at least 20 and 500 km, respectively (Lehtonen, Havia, Kovanen, Leminen, & Saure, 2016). To quantify the total annual distance pedaled (d_t), the following equation was adopted based on the self-reported data collected:

$$\mathrm{d}_t = [(Q_2 \times Q_3) \times 52]$$

where Q_2 is the weekly cycling rate and Q_3 is the daily mileage, and 52 the number of weeks per year. The *inactive-cyclists* group ($n = 20$) was composed of participants who reported the ability to ride a bicycle; however, they had not practiced urban cycling for at least the last 10 years. The participants in this group were physically active and engaged in some type of moderate/intense aerobic physical activity, except cycling, at least three times a week (Dantas et al., 2009; Lehtonen et al., 2016). Data from one active-cyclist and two inactive-cyclists were missing due to equipment failure, hence the final number of participants included in the data analysis was 37. Table 1 presents their characteristics. All participants had normal or corrected-to-normal vision (i.e., score range of 20/20 to 20/30 on the Snellen visual acuity test), absence of sensorimotor impairments, neurotypical system, and were within the height and weight ranges of 160–180 cm and 60–80 kg, respectively. The protocol was approved by the São Paulo State University Ethical Committee (CAAE: #08411519.1.0000.5398) and conducted according to the principles of the Declaration of Helsinki. Participants signed informed consent prior to the start of the experiment.

2.2. Apparatus

A South Hunter GT 29″ (South Bike), 21 gears, frame size 17 and mechanical disc-brake system was used in this study. The frame size was suitable for the height of all participants and the saddle was individually adjusted so that participants could comfortably reach the ground with their toes while sitting on the bicycle. The braking task was recorded using a GoPro camera (Hero 3) at a sampling rate of 60 Hz and resolution of 1920 × 1080. A white spherical marker was attached to the head tube of the bicycle for motion tracking purposes (Fig. 1a). Data from GoPro videos was used to calculate the rate of deceleration over time. To assess brake adjustments, Hall-effect sensors (US1881/U18) were attached on the handlebar grips and magnets fixed to the brake levers (right-brake and left-brake). These sensors are commonly used to determine the position of an object based on a magnetic field (Ramsdem, 2011; Jezný & Čurilla, 2013; Saha et al., 2017). The calibration of the Hall-effect sensors involved three steps: i) positioning, verify the position and orientation of the sensors and the magnets on the bicycle; ii) baseline, one-minute baseline data recording without any brake lever interference; iii) testing, one-minute test recording, starting with both brakes fully released, followed by fully pressing the right brake, releasing it, and next fully pressing the left brake, releasing it. The magnetic flux exhibited a direct proportionality to the displacement of the brake levers, ranging from 210 GAUSS (fully released) to 580 GAUSS (fully pressed). After confirming these values, the data collection was initiated. The brake sensors were connected to an Arduino-UNO (R3) system installed in a black box fixed at the center of the handlebar (Fig. 1a). By using analog-to-digital feature, the Arduino converted the magnetic flux voltage to a numerical output and transmitted it to a smartphone (SM-A305GT, Android 11) via an USB cable, where the output was stored in a Serial USB Terminal app (Kai Morich, version 1.45). Data from the magnetic sensors were used to provide data regarding participants' control of the brakes (i.e., onset and adjustments) during the test.

2.3. Procedure and design

The data collection took place in the sports hall of the Department of Physical Education at São Paulo State University, Bauru, Brazil. A linear cycle path (1 m-width, 37 m-long) was demarcated on the floor by an adhesive yellow/black tape (Fig. 1b). The cycle path was divided into two zones: the approaching zone, from the initial distances to the beginning of a black mat; and the stopping zone, beginning at the black mat until the obstacle at the end of the path. Two initial distances were used to manipulate cycling speed (Rodrigues et al., 2006): *i) short-initial-distance*, initial distance at 21.6 m from the obstacle; and *ii) long-initial-distance*, initial distance at 37 m from the obstacle. The differences in maximum velocity were aimed at varying task demands, that is, a higher speed would result in less time available to stop. To avoid accidents caused by skidding during braking, a black anti-slip mat (2 mm-thick, 1 m-width, 14 m-long) was placed in the stopping zone. The obstacle (0.81 m-height, 0.05 m-width, 0.15 m-long) placed at the end of the cycle path, blocking the path, was made of foam. Prior to the beginning of the braking test, participants had 5 min to familiarize with the bicycle, experimental setting, and task instructions.[1] Participants were asked to accelerate the bicycle as fast as possible until they reached the stopping zone, from which they were free to initiate braking, aiming to stop as close as possible to the obstacle and to avoid the collision. To synchronize the brake sensors with the video recordings, participants were asked to start each trial with fully-pressed brakes and, on the experimenter's command, release the brake levers as fast as possible and immediately start accelerating the bike. Bicycle weight was manipulated to change maximum deceleration (Fajen, 2005c, 2005a; Skrucany et al., 2020). Loads of 5 kg and 10 kg were added to the bicycle frame (i.e., inserted in a cargo bag attached to the frame (Fig. 1a) to create the following load conditions:

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[1] Participants also wore eye tracking glasses (Mobile Eye-5 glasses, ASL) during the experiment. The results from gaze analysis, however, will be discussed in a subsequent paper.

Table 1
Means (SDs) for characteristics of the participants (n = 37) by experimental group.

	Active-cyclists (n = 19)	Inactive-cyclists (n = 18)
Age (years)	29.42 (6.28)	29.50 (3.83)
Weight (kg)	74.60 (7.10)	77.10 (10.10)
Height (m)	174.26 (5.72)	179.78 (5.96)
Weekly distance pedaled (km)	46.42 (17.47)	N/A
Annual distance pedaled (km)	2244.84 (884.64)	N/A

N/A refers to not applicable.

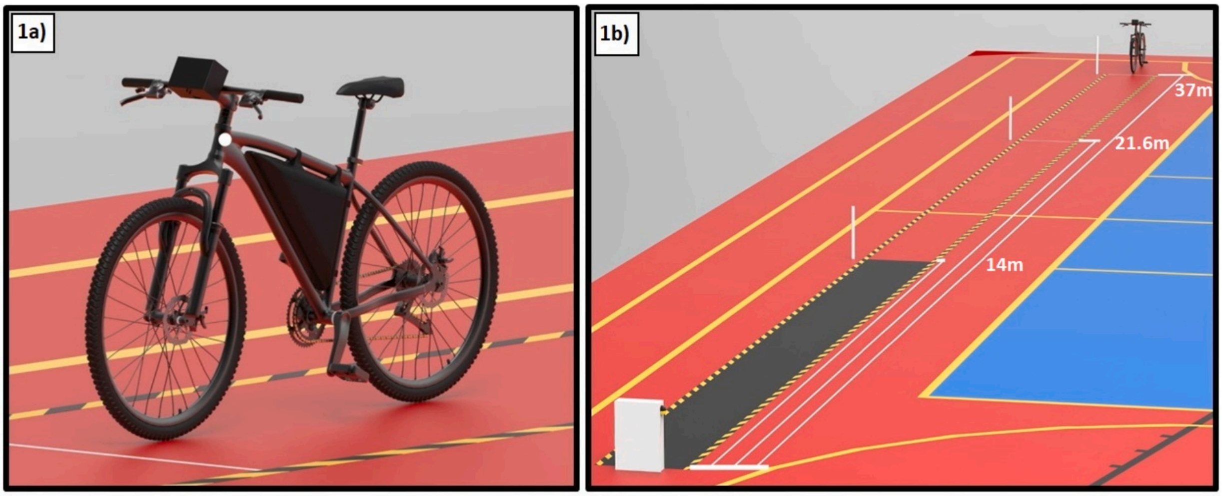

Fig. 1. a) computer-generated image of the experimental bicycle with the cargo bag attached to the frame, the Arduino controller box at the handlebar, and the white spherical marker for motion tracking purposes; b) computer-generated image representing the approaching (red floor) and stopping (black mat) zones of the cycle path and the foam obstacle (white cuboid). Initial distances placed at 21.6 m and 37 m to the obstacle were used for short-initial-distance and long-initial-distance conditions, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

i) no-load, the bicycle without additional loads; *ii) 5 kg-load*, the bicycle with the addition of 5 kg; *iii) 10 kg-load*, the bicycle with the addition of 10 kg. In each load condition block, four trials were performed in short-initial-distance and four in long-initial-distance condition, eight trials per block, totalizing 24 trials. The order of blocks and trials were randomized. A three-minute interval between the blocks was given to avoid participants from becoming physically fatigued. The bicycle loading manipulation was performed so that the participant did not notice it. No participant reported awareness of a change in the bicycle weight during data collection.

2.4. Data analysis

Prior to data processing, GoPro radial distortion was corrected from the videos using algorithms based on the Hough transformation (Santana-Cedrés et al., 2016; Vieira et al., 2017). The software is a command-line tool, running in Ubuntu Linux (18.04.3 LTS), that estimates the lens distortion model from a single frame of the original video and creates its undistorted version. The trajectory of the bicycle was tracked frame-by-frame using the Kinovea software (version 0.9.1). Prior to data collection, we positioned two cones to delineate the starting and ending points of the cycle path. The initial cone was aligned so that its basis's upper right corner (viewed from the top) precisely coincided with the starting line, while the final cone was placed at the end line with its upper left corner (viewed from the top). The two corners precisely denoted a distance of 37 m. A one-minute video recorded these cones as spatial reference points for calibration in the subsequent tracking analysis using Kinovea software. Following the data collection phase, the cones were removed from the cycle path to carry out the braking test. Post-collection, the calibration involved marking the distance between the two cones to set the video scale, ensuring accurate measurements corresponding to real-world dimensions. This process was repeated for each video before initiating any tracking analysis. The digitized coordinates were passed through a low-pass filter (second-order Butterworth) to remove noise (Winter, 2009). Total horizontal displacement of the bicycle was computed for each participant in each trial and exported as tabular data in CSV format. Algorithm collections for signal processing and variables calculation were developed using MATLAB software (The MathWorks Inc., USA, version R2018b). The following dependent variables were derived: *Speed manipulation check:* maximum velocity (m/s) was calculated by identifying the highest peak on the velocity curve across the trial. *Braking performance:* first, the number of trials with a collision with the obstacle (soft touches were also included) was counted in each condition. Second, the final stopping distance from the obstacle was determined by taking the distance (m) between the front edge of the front wheel and the obstacle in the final frame (i.e., bicycle velocity reached zero). The mean and SD final stopping distance (m) served as dependent variables. *Control strategy:* the analysis of braking and the regulation of deceleration was based on Fajen's studies (2005a; 2005c). From the total horizontal displacement, we derived several parameters for every frame, including the distance from the obstacle (Z), the velocity (V) and the deceleration (D) of the bicycle. Moreover, for each frame, the following variables were also calculated: the momentary deceleration, that is the current deceleration (Dcurrent) and the ideal deceleration (Dideal), that is the constant rate of deceleration required to exactly stop at the obstacle without making any further adjustments (see Appendix B for details). The observed maximum deceleration (obsDmax) was measured by taking the maximum value of Dcurrent in each bicycle load condition. Brake adjustments were identified when the distance between the magnets (brake levers) and hall-effect sensors (handlebar grips) changed. The magnetic flux was directly proportional to the brake levers displacements, ranging from 210 GAUSS (fully released brakes) to 580 GAUSS (fully pressed brakes). Brake displacement data was then normalized, with 0 attributed to fully released brakes and 1 indicating fully-pressed brakes (or maximum brake displacement). Brake adjustments were identified, using the MATLAB's function 'findchangepts', by the mean and the slope of the signal changing abruptly with a minimum residual error increase of 0.1 (i.e., 10% of maximum brake displacement as in Fajen, 2008). Brake adjustments that resulted in increases in deceleration (brake displacement >0.1), were computed as 'positive' adjustments; decreases (brake displacement < -0.1) and holds ($0.1 <$ brake displacement > -0.1) in deceleration were counted as 'negative' and 'no' adjustments, respectively. Only 'positive' brake adjustments were included in the subsequent analyses (Fajen, 2005a). Braking onset (s) was defined as the moment of the first brake adjustment. We identified the value of Dideal at braking onset (measured in m/s^2). To examine whether control was based on affordances, we also expressed Dideal at brake onset in units of observed maximum deceleration (% obsDmax). Each brake adjustment occurs at a specific value of Dideal and to examine the relation between magnitude of brake adjustment and Dideal, brake adjustments were grouped into four equally spaced bins (or intervals) of Dideal (m/s^2). The bins ranged from zero to the maximum Dideal. Following Fajen's study (Fajen, 2005a), we only considered Dideal bins in which the deceleration error was between -14.28% and 14.28% of obsDmax.[2] Magnitude of brake adjustments for each Dideal bin was calculated. *Styles of braking:* Initial perusal of the data showed that participants indeed adopted different styles of braking (Fig. 4a). We classified each individual trial into one of three styles of braking control based on the unfolding of Dideal and Dcurrent during the trial. The three styles were identified according to the shape of Dideal and Dcurrent curves as: *i) aggressive style*, the Dideal curve shows a skewed parabolic shape and its peak occurs near the end of the trial and Dcurrent shows a higher peak just after the Dideal peak (i.e., active braking is initiated late and high decelerations are achieved briefly before the stop); *ii) conservative style*, the Dideal curve grows linearly and flattens near the end of the trial, and Dcurrent shows frequent, small local peaks (i.e., gradual braking is initiated early and a moderate rate of deceleration is maintained until the stop); *iii) other*, mostly Dideal and Dcurrent show an early peak with multiple local peaks for Dcurrent until the end of the trial (i.e., braking is initiated earlier but with high variations, resulting in Dideal oscillating erratically). Based on the above description two raters (GG, JvdK) independently categorized each trial for each participant. Cohen's Kappa reliability test was performed to measure the level of agreement between two raters in classifying the style of braking. In the initial round, Cohen's κ indicated a moderate agreement between the two raters, $\kappa = 0.730$, $p < .001$. To further increase agreement, the two raters reviewed the plots together to reach an agreement on the remaining discrepancies. Next, categorization was further verified by calculating r^2 values for fitting polynomial curves of 1st, 2nd and 3rd order of the Dideal. If the r^2 for 2nd order polynomial was closer to the r^2 for the 3rd order polynomial than to r^2 for the 1st order polynomial, the trial was categorized as an aggressive style; if the r^2 value for the 2nd order polynomial was closer to the r^2 on the 1st order polynomial then the trial was categorized as a conservative braking style. In doing so, the categories conservative and other were combined into one conservative category. There was a strong agreement between the classification by the two raters and the classification using the polynomial fitting procedure, $\kappa = 0.949$, $p < .001$. Frequency distribution of braking styles was computed across conditions for all participants. To provide a more comprehensive characterization of the styles, the dependent variables observed maximum deceleration and braking onset were used.

2.5. Statistical analysis

The Shapiro Wilk normality test was conducted on all dependent variables. For the parametric variables, group (active-cyclists, inactive-cyclists) by bicycle load (no-load, 5 kg-load, 10 kg-load) by initial distance (short-initial-distance, long-initial-distance) analyses of variance with repeated measures (RM-ANOVA) on the last two factors were conducted. In case the assumption of normal distribution was violated, a generalized estimating equation (GEE) method was conducted under same factorial effects. *Speed manipulation check:* maximum velocity was submitted to a GEE analysis. *Braking performance:* percentage of collisions, final stopping distance, and SD final stopping distance were submitted to GEE analyses. *Control strategy:* observed maximum deceleration was submitted to an RM-ANOVA. Dideal at braking onset (in m/s^2) and Dideal at braking onset (in % obsDmax) were submitted to GEE analyses. In addition, multiple linear regression analyses were conducted for each group separately to examine whether the magnitude of brake adjustments was predicted by ideal deceleration and/or load conditions. *Styles of braking:* Chi-square, and McNemar's and Cochran's Q tests were conducted to examine whether the distribution of braking styles differed by group, bicycle load, and cycling speed and/or interactions between the factors, respectively. Additionally, braking onset and observed maximum deceleration were submitted to GEE analyses with styles of braking (aggressive style, conservative style) as a factor. Statistical analyses were run using

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[2] Deceleration error is the difference between Dideal and Dcurrent at each instant. In the article by Fajen (2005a), the deceleration error was considered 'nulled' whenever it remained between –1.0 and 1.0 m/s^2, that is, 14.28% of the maximum deceleration used (7 m/s^2). As the range of deceleration of a bicycle is substantially smaller than that of cars (Fajen's protocol), the relative deceleration error was adopted in the present study.

SPSS Statistics (17.0.1). Tukey Honestly Significant Difference tests and Greenhouse-Geisser degrees of freedom adjustments were conducted when necessary. The value alpha was set at 0.05. Effect sizes were calculated using Partial Eta Squared with 0.02 or less, 0.06, and 0.14 or more, representing small, medium, and large effect sizes, respectively (Cohen, 1988).

3. Results

3.1. Speed manipulation check

For the maximum velocity, GEE revealed a main effect of load ($\chi2 = 67.031$, $p < .001$) and initial distance ($\chi2 = 379.334$, $p < .001$), indicating that participants indeed reached a greater maximum velocity in the long-initial-distance condition (M = 6.11; SE = 0.180 m/s) than in the short-initial-distance condition (M = 4.09; SE = 0.083 m/s). In addition, participants pedaled faster in no-load (M = 5.198; SE = 0.131 m/s) than in the 5 kg-load (M = 5.11; SE = 0.132 m/s) and 10 kg-load conditions (M = 5.00; SE = 0.129 m/s). No effects for group were present.

3.2. Braking performance

Participants of both groups did almost always manage to stop in time, resulting in a low number of collisions that were independent of initial distance and load (Fig. 2a). Yet, the GEE indicated a main effect of initial distance for final stopping distance ($\chi2 = 52.673$, $p < .001$), indicating that participants stopped farther from the obstacle in the long-initial-distance than short-initial-distance condition (Fig. 2b). Finally, for the SD final stopping distance, a main effect of group ($\chi2 = 7.541$, $p = .006$) and an interaction between group, load, and initial distance ($\chi2 = 6.191$, $p = .045$) were revealed. Post-hoc comparisons indicated that the inactive-cyclists group showed larger variability in the final stopping distance than the active-cyclist, but only in the 10 kg-load short-initial-distance condition (Fig. 2c).

3.3. Control strategy

Fig. 3a shows that loading the bicycle did not systematically decrease the observed maximum deceleration across the two groups. Instead, RM-ANOVA revealed main effects of initial distance, $F(1,35) = 70.067$, $p < .001$, $\eta_p^2 = 0.667$, and an interaction between group, load and initial distance, $F(2,70) = 3.341$, $p = .050$, $\eta_p^2 = 0.087$. Post-hoc comparisons indicated only differences in the observed maximum deceleration for the inactive-cyclists. In the short-initial-distance condition they showed higher observed maximum deceleration in the no-load condition than in the 5 kg-load and 10 kg-load conditions. Following Fajen (2005c), we then tested if Dideal at braking onset (in m/s^2) different depending on loading, and if so, whether these differences would disappear when scaling Dideal to maximum deceleration (in % obsDmax). No differences were found for both Dideal at braking onset (in m/s^2) and Dideal at braking onset (in % obsDmax) across load conditions.

We also examined if brake adjustments are relative to maximum deceleration or to null error from ideal deceleration. Accordingly, we analyzed brake adjustments as a function of ideal deceleration only for intervals where the difference between current and ideal deceleration is approximately zero (and hence, no systematic brake adjustments are predicted from error-nulling models). The multiple linear regression revealed significant models for both the active-cyclists, $F(2,11) = 48.286$, $p < .001$, $R2 = 0.915$, and the inactive-cyclists, $F(2,11) = 48.796$, $P < .001$, $R2 = 0.916$. For both analyses, the magnitude of brake adjustments was significantly predicted by ideal deceleration, $p < .001$, but not by load conditions. The slopes of the regression line (Fig. 3b) were significantly steeper than zero

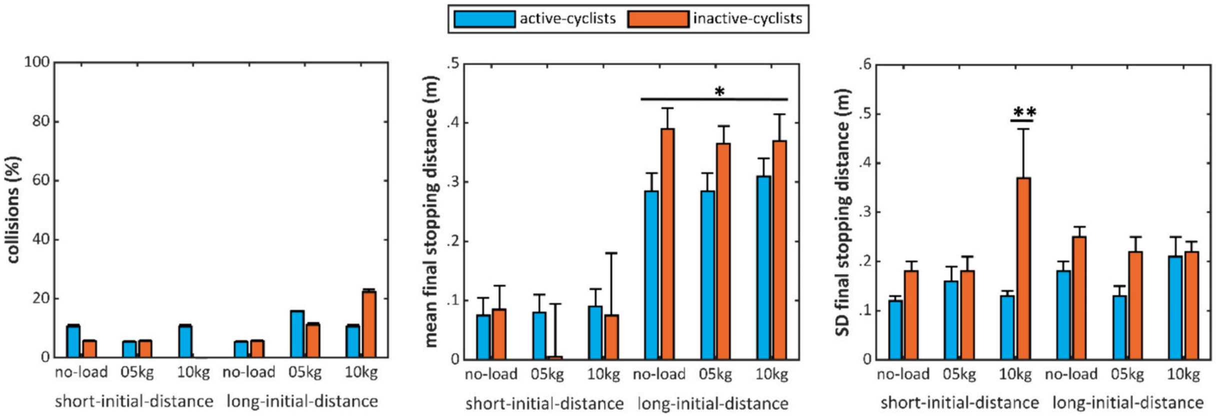

Fig. 2. a) percentage of collisions, b) average final stopping distance and c) average within-subject SD final stopping distance across initial distance and load for active-cyclists (blue bars) and inactive-cyclists (red bars). *Significant main effect of initial distance; **Significant interaction between group, load, and initial distance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

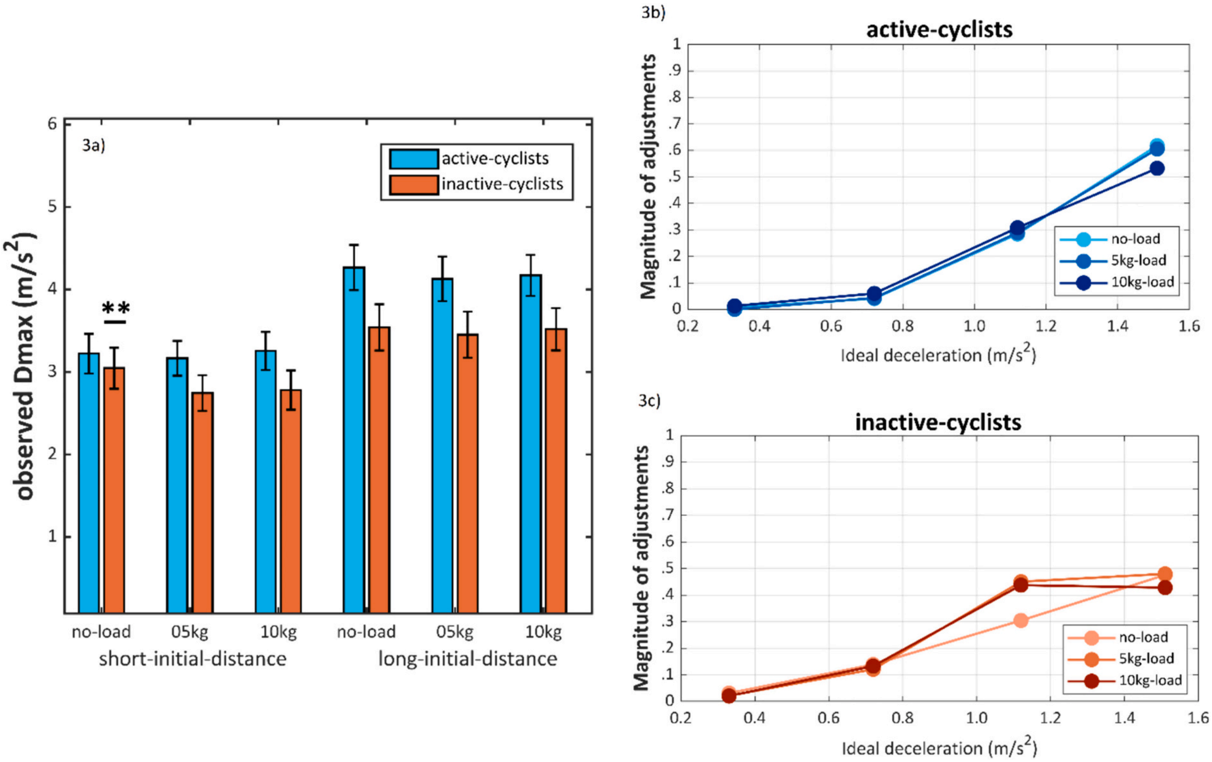

Fig. 3. a) observed maximum deceleration across load and initial distance for active-cyclists (blue bars) and inactive-cyclists (red bars); b) magnitude of brake adjustments as a function of ideal deceleration by load conditions for active-cyclists; and c) for inactive-cyclists. All frames used in this analysis showed a deceleration error close to zero (or 'nulled'). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for both the active-cyclists ($B = 0.503$, $t = 9.826$, $p < .001$) and the inactive-cyclists ($B = 0.401$, $t = 9.871$, $p < .001$), indicating that magnitude of brake adjustments depended on ideal deceleration, regardless of load condition.

3.4. Styles of braking

The frequency distribution of the aggressive and conservative styles of braking is showed in Fig. 4b. Chi-square analysis showed a significant association between the style of braking and group, $\chi^2\,(1) = 22.42, p < .001$. The odds ratio indicated that the proportion of aggressive style was 4.25 times higher among the active-cyclists compared to the inactive-cyclists. McNemar's and Cochran's tests were used to compare distribution of braking styles across initial distance and load conditions, respectively. McNemar's test revealed that there was no significant difference in the distribution of braking styles across the initial distance conditions, $p = .332$. Likewise, Cochran's Q test showed no significant difference in the distribution of braking styles between the load conditions, $\chi^2\,(2) = 4.000, p = .135$). GEE analysis confirmed significant differences in braking onset ($\chi^2 = 8.291, p = .004$) and observed maximum deceleration ($\chi^2 = 45.059$, $p < .001$) between the braking styles. The aggressive style was associated with later braking onset and reached higher observed maximum deceleration compared to the conservative brakers (Fig. 4c).

4. Discussion

This study investigated how active- and inactive-cyclists regulate brake adjustments to succeed in a collision avoidance task. We adapted the virtual braking protocol used by Fajen (Fajen, 2005a, 2005c, 2008) to assess cyclists' behaviors in an in-situ experiment, that is, participants were asked to ride a conventional mountain bike in a gymnasium and stop as close as possible to an obstacle. Extra loads were added on the bicycle, to manipulate braking capabilities, in which a heavier bike was expected to reduce the maximum achievable deceleration. Task demands were manipulated by using different initial distances such that maximum velocity at braking onset and the time available to stop were varied. We found that participants stopped farther away in front of the obstacle when approaching with long-initial-distance compared to an approach with short-initial-distance, whilst no differences were found across load conditions. Yet, both the inactive- and the active-cyclists were largely successful in following task instructions and showed equally low number of collisions, although the inactive cyclists did show a higher variability in stopping distance to the obstacle. We found partial evidence that both groups regulated braking in accordance with an affordance-based control strategy but achieved this using different styles of braking, irrespective of load condition.

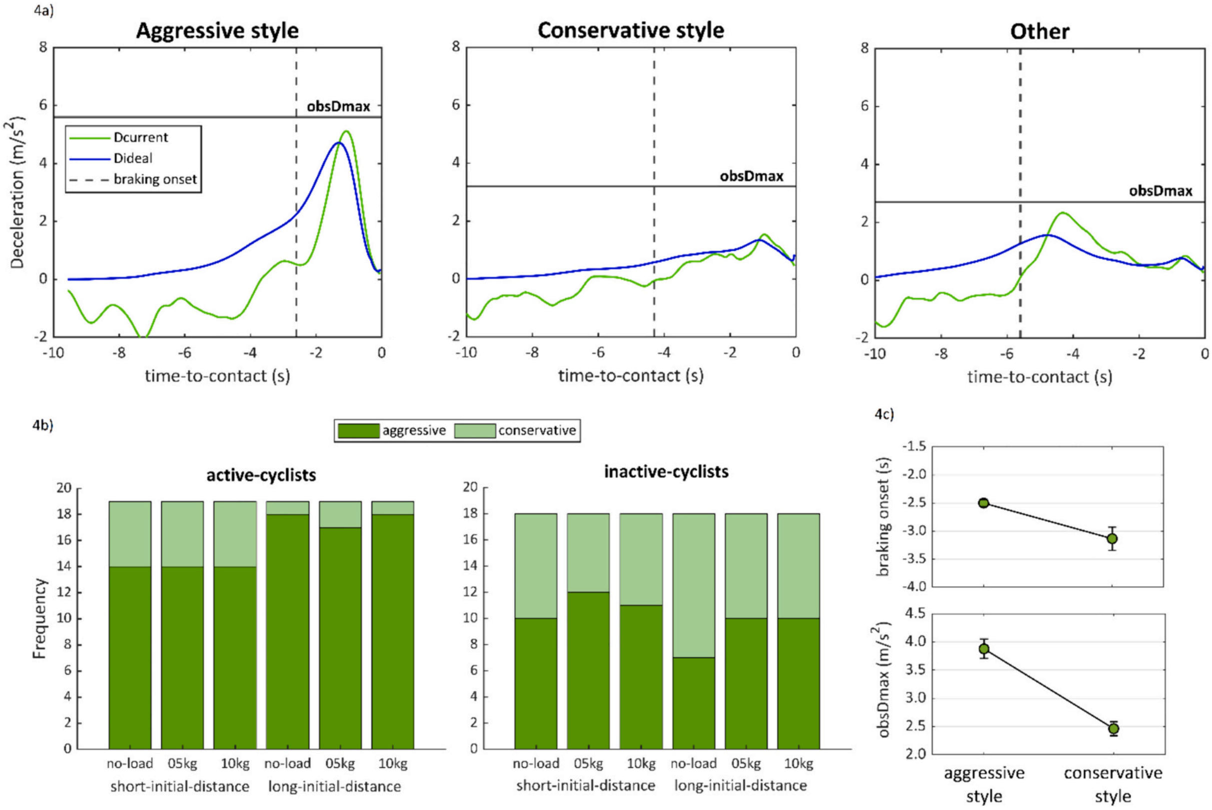

Fig. 4. a) Styles of braking control: i) aggressive style, Dideal curve shows a skewed parabolic shape, with a late braking onset and a high and steep peak; ii) conservative style, Dideal curve grows linearly flat and low peak; and iii) other, early peak decelerations with multiple subsequent local peaks for Dideal and Dcurrent; b) Frequency of braking styles per group across load and initial distance conditions. c) braking onset and observed maximum deceleration (obsDmax) by styles of braking.

4.1. Control strategy

First, to test the effects of changing action capabilities on brake adjustments in-situ, we added extra loads to the bike to change braking capabilities, with the heaviest load predicted to reduce the observed maximum deceleration the most. Yet, no evidence was forthcoming that loading the bicycle systematically decreases the observed maximum deceleration. Only for the inactive-cyclists in the short-initial-distance condition, the observed maximum deceleration was found to be higher in the no-load condition than in the 5 kg-load and 10 kg-load conditions. In addition, the results also did not confirm that cyclists would initiate braking at lower values of ideal deceleration (i.e., Dideal in m/s^2) with the extra load. We found no evidence that the current loading systematically affected participants' control of braking. Consequently, we were unable to test whether the differences in ideal deceleration would disappear when scaling to participants' action capabilities, that is, when is expressed in maximum deceleration (i.e., Dideal in % obsDmax) as is predicted for affordance-based control (Fajen, 2005c). A possible explanation for the lack of differences in loading may relate to the positioning of the loads on the bicycle. We added the loads of 5 kg and 10 kg in a cargo bag on the bicycle frame, close to the individual-bicycle center of mass (Fig. 1a). To prevent participants' awareness of the manipulation, the addition or removal of the loads to the bicycle were performed in a separate environment. Only 2 of the 37 participants reported that something changed on the bike, but they were unable to point out what exactly had changed. This demonstrates that participants remained largely unaware of the manipulation. However, placing the loads close to the individual-bicycle center of mass may have reduced potential disturbances to the braking power. Skrucany et al. (2020) found that adding front-loaded weight to a car significantly reduced braking power compared to center- or rear-loaded weights. Nonetheless, we added 5 kg and 10 kg to the bicycle frame, representing approximately 5% to 15% of the individual-cycle total weight, respectively, while the loads Skrucany et al. (2020) ranged between 10% to 40% of the car's mass. Unlike Skrucany et al. (2020), we did not observe that the extra loads perturbed braking, indicating that future studies should consider both the positioning of loads and use heavier loads. Alternatively, braking on different slopes (e.g., uphill versus downhill) or under physical fatigue may be feasible protocols for empirical studies to investigate that braking in cycling is scaled to action capabilities as presumed in affordance-based control.

Second, to investigate whether cyclists use an affordance-based strategy to control braking, we also examined if brake adjustments occurred when the difference between current and ideal decelerations was close to zero (i.e., deceleration error is nulled) (Fajen, 2005a). An error-nulling strategy anticipates no further brake adjustments if current acceleration equals or approaches ideal deceleration, while affordance-based control predicts increased magnitude of brake adjustments as ideal deceleration surges and (thus) gets closer to the action boundary. Indeed, the multiple linear regression analysis revealed that participants did increase the magnitude of brake adjustments as the ideal deceleration increased (Fig. 3b and 3c), regardless of group and load condition. This corroborates previous findings (Fajen, 2005a, 2005c) and provides evidence that participants adopted an affordance-based control strategy for braking regulation in cycling. That is, brake adjustments are scaled to action capabilities in such a way that ideal deceleration is kept within the action boundaries rather than to null the deceleration error (Fajen, 2005a, 2005c, 2007). This is the first study to provide evidence that cyclists regulate braking in-situ by sustaining the perception of stop-ability. Previously, Rodrigues and colleagues (Rodrigues et al., 2006, 2012) found support for cyclists using an error-nulling strategy (i.e., the constant tau-dot) in collision avoidance braking. However, those studies did not capture how the use of tau-dot is grounded in the cyclists' action capability. This is a critical constraint for control of braking when studied from an ecological psychology approach (Fajen, 2005a, 2005c, 2007, 2008). Yet, while Fajen used virtual environments to show this for car driving, we extend this work to in-situ environments, in which the grounding of control in action (capabilities) is arguably much more precarious. In sum, even though the load manipulation was insufficiently effective to allow us to fully address the objectives of the study, we do find partial evidence that the control of braking is the affordance-based. In particular, we demonstrate that systematic adjustments in magnitude of braking adjustments occurred, even when the system was in the ideal action state. Our results thus indicate that cyclists avoid collisions by making adaptive brake adjustments that keep ideal deceleration below the maximum achievable deceleration rather than nulling the deviation with ideal deceleration. Therefore, despite the absence of significant load-related effects on observed maximum deceleration and brake adjustments, the study provides initial evidence supporting participants' use of an affordance-based control strategy.

4.2. Styles of braking

Finally, we sought evidence whether cyclists would show different styles of control in an in-situ braking in cycling. Affordance-based control holds that the primary constraint on successful braking is to keep the ideal deceleration required to stop below the maximum deceleration. Within this constraint, however, different braking styles are still enabled. We expected that experience may invite different styles with active-cyclists feeling safer and more in control, and thus more likely to adopt an aggressive style of braking, that is, performing closer to their maximum action capabilities, when compared to inactive-cyclists. Indeed, we identified two braking styles: an aggressive style, characterized by a late braking onset and a high, steep peak in ideal deceleration and a more conservative style, characterized by an early braking onset and a gradual, linear increase in ideal deceleration. The aggressive braking style was more prevalent among active-cyclists compared to inactive-cyclists. This result confirms our hypothesis that the more experienced individuals act closer to their action boundaries (Dicks et al., 2010; Fajen, 2005b, 2007; Higuchi et al., 2011; Seifert et al., 2021; Zheng et al., 2021). For example, Zheng et al. (2020) showed that both less and high skilled football goalkeepers considered their action capabilities (i.e., the minimum time they needed to reach the ball) when trying to stop a penalty kick, but the high skilled goalkeepers acted closer to their action boundary. That is, they started the dive when the required velocity to reach the ball equals to the maximum

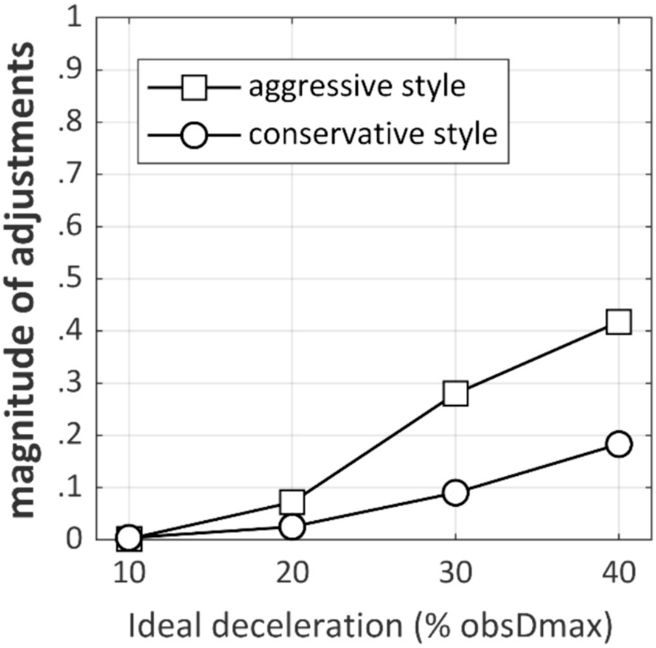

Fig. 5. Magnitude of brake adjustments as a function of ideal deceleration (in percentage of observed maximum deceleration) for the two braking styles.

dive velocity they can achieve, which translated in coordinating the dive onset with the moment the kicker's non-kicking leg landed next to the ball (Zheng et al., 2021; see also van der Kamp et al., 2018). Possibly, experience or exposure enhances the sensitivity to the action boundaries, allowing them to act closer to the boundaries without going beyond them. We suggest that the different styles of braking reflect differences in the calibration between information and action (Bingham & Pagano, 1998; Fajen, 2005b, 2007). Fig. 5 illustrates this reasoning (see also Fajen, 2005c, and Fig. 3b and 3c above). It shows the magnitude of brake adjustments as a function of ideal deceleration, with the latter being scaled to the observed maximum deceleration (% obsDmax) for the two braking styles. Because the brake adjustment is normalized (i.e., 0 representing fully released brakes and 1 indicating fully-pressed brakes), we can directly compare how the perceived ideal deceleration in units of maximum deceleration scales to the magnitude of brake adjustments in units of maximum brake displacement. Separate multiple linear regression analysis for each braking style confirmed that the magnitude of brake adjustment was significantly predicted by ideal deceleration in units of observed maximum deceleration, p's < 0.001. Importantly, the slope of the regression is found to be significantly larger for the more aggressive style compared to the conservative style, $t = -4.604$, $p < .001$. This indicates that perceived ideal deceleration has a stronger impact on the brake adjustments for the aggressive style of braking than for the conservative braking style, which points to a difference in calibration.

It is noticeable that although closer, even the cyclists using an aggressive style remained relatively distant from their maximum action boundary. That is, irrespective of braking style, participants regulated brake adjustments such that they typically did not exceed an ideal deceleration of 40% of the observed peak deceleration across the trials of individual participants (Fig. 5). In comparison, Fajen (2005c) reported that, in a car simulator, drivers only started to increase brake adjustments when the ideal deceleration had reached at least ~75% of the maximum deceleration. This discrepancy is perhaps not unexpected as in an in-situ braking there is a real risk of physical damage following a collision compared to braking in a virtual environment. Hence, the cyclists in the current study would have been more cautious (or conservative) than participants in the study by Fajen (2005c). By taking the maximum deceleration as reference, braking is regulated in relation to critical boundaries (i.e., demarcating possible from impossible action). Yet, traffic users navigating in real-traffic environment may opt to act relative to their preferred rather than critical boundaries instead (i.e., demarcating preferred from non-preferred actions). In this respect, Warren (1984) demonstrated that individuals using stair climbers could accurately perceive critical boundaries (i.e., relative ratio between the riser height and the leg length), but at the same time preferred riser heights with lower ratios, presumably because at these ratios they expended less energy. Analogously, cyclists in our study may have opted for a preferred action boundary that is lower, more conservative than the critical boundary, as it increases safety. Additionally, Vansteenkiste, Cardon, D'Hondt, Philippaerts, and Lenoir (2013) reported that cyclists' gaze strategies differed from the gaze strategies observed in car drivers. In cyclists gaze depended on cycling speed and lane width, with gaze fixations being more distant at higher speeds. An important question to explore is whether the differences in braking styles that we observed are associated with distinct gaze strategies; if, for example, a more distant gaze invokes a more aggressive braking style (or vice versa).

4.3. *Strengths and limitations of the study*

This study extends Fajen's research on affordance-based control of action from virtual to in-situ environments, where control in action is more challenging and impactful. This is a significant strength, enhancing the validity of affordance-based control to real-world contexts. Except for reproducing Fajen's findings on affordance-based control in (Fajen, 2005a, 2005c) to cyclists in-situ, the novelty of our work also lies in revealing how different styles of braking emerge.

The manipulation of observed maximum deceleration through bicycle loading did not yield the anticipated results. We determined the observed, or achieved, maximum deceleration by identifying the highest peak of current deceleration that each participant reached in each load condition. This is likely to be an underestimation of the real – or achievable - maximum deceleration. Thus, our methodology assessed the maximum achieved deceleration but did not allow us to ascertain the maximum achievable deceleration. Further investigations should incorporate a separate maximum braking test into the protocol, for instance, by asking participants to stop as fast as possible (while safety must be ensured, of course). Additionally, determining the specific dynamics of the experimental bicycle beforehand, while also considering established braking system standards such as DIN 79010 or ISO 4210-2, would help strengthen the manipulation of braking capabilities in in-situ cycling experiments, without neglecting cyclist safety.

5. Conclusions

In summary, the results of this study confirm that cyclists avoid collisions by making adaptive brake adjustments that keep ideal deceleration below the maximum achievable deceleration rather than nulling the deviation with ideal deceleration. This is the first study showing the control of braking in an in-situ cycling experiment is affordance-based, that is, braking is controlled by sustaining the perception of stop-ability. While the cyclists adopted the same affordance-based control strategy, they did use different braking styles ranging from aggressive to conservative. The use of the styles was associated with participants cycling experience and are suggested to emerge from differences in calibration between perception and action.

CRediT authorship contribution statement

Gisele C. Gotardi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **John van der Kamp:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Martina Navarro:** Writing – review & editing. **Geert J.P. Savelsbergh:** Supervision. **Sérgio T. Rodrigues:** Writing – review & editing, Resources, Funding acquisition.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2024.103225.

References

van Andel, S., Cole, M. H., & Pepping, G. J. (2017). A systematic review on perceptual-motor calibration to changes in action capabilities. *Human Movement Science, 51*, 59–71. https://doi.org/10.1016/j.humov.2016.11.004

Andersen, G. J., Cisneros, J., Atchley, P., & Saidpour, A. (1999). Speed, size, and edge-rate information for the detection of collision events. *Journal of Experimental Psychology. Human Perception and Performance, 25*(1), 256–269.

Bingham, G. P., & Pagano, C. C. (1998). The necessity of a perception–action approach to definite distance perception: Monocular distance perception to guide reaching. *Journal of Experimental Psychology: Human Perception and Performance, 24*(1), 145–168.

Blau, J. J., & Wagman, J. B. (2022). *Introduction to ecological psychology: A lawful approach to perceiving, acting, and cognizing*. Taylor & Francis.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Academic press.

Dantas, J. L., Smirmaul, B. P. C., Altimari, L. R., Okano, A. H., Fontes, E. B., Camata, T. V., & Moraes, A. C. (2009). The efficiency of pedaling and the muscular recruitment are improved with increase of the cadence in cyclists and non-cyclists. *Electromyography and Clinical Neurophysiology, 49*(6), 311.

Dicks, M., Davids, K., & Button, C. (2010). Individual differences in the visual control of intercepting a penalty kick in association football. *Human Movement Science, 29*(3), 401–411. https://doi.org/10.1016/j.humov.2010.02.008

Fajen, B. R. (2005a). Calibration, information, and control strategies for braking to avoid a collision. *Journal of Experimental Psychology: Human Perception and Performance, 31*(3), 480–501. https://doi.org/10.1037/0096-1523.31.3.480

Fajen, B. R. (2005b). Perceiving possibilities for action: On the necessity of calibration and perceptual learning for the visual guidance of action. *Perception, 34*(6), 717–740. https://doi.org/10.1068/p5405

Fajen, B. R. (2005c). The scaling of information to action in visually guided braking. *Journal of Experimental Psychology: Human Perception and Performance, 31*(5), 1107–1123. https://doi.org/10.1037/0096-1523.31.5.1107

Fajen, B. R. (2007). Affordance-based control of visually guided action. *Ecological Psychology, 19*(4), 383–410.

Fajen, B. R. (2008). Perceptual learning and the visual control of braking. *Perception & Psychophysics, 70*(6), 1117–1129. https://doi.org/10.3758/PP.70.6.1117

Gibson, J. J. (1979). *The ecological approach to visual perception*. Routledge.

Harrison, H. S., Turvey, M. T., & Frank, T. D. (2016). Affordance-based perception-action dynamics: A model of visually guided braking. *Psychological Review, 123*(3), 305.

Higuchi, T., Murai, G., Kijima, A., Seya, Y., Wagman, J. B., & Imanaka, K. (2011). Athletic experience influences shoulder rotations when running through apertures. *Human Movement Science, 30*(3), 534–549. https://doi.org/10.1016/j.humov.2010.08.003

van Hof, P., van der Kamp, J., & Savelsbergh, G. (2008). The relation between infants' perception of catchableness and the control of catching. *Developmental Psychology, 44*, 182–194.

van der Kamp, J., Bennett, S. J., Savelsbergh, G. J., & Davids, K. (1999). Timing a one-handed catch: II. Adaptation to telestereoscopic viewing. *Experimental Brain Research, 129*, 369–377.

van der Kamp, J., Dicks, M., Navia, J. A., & Noël, B. (2018). Goalkeeping in the soccer penalty kick: It is time we take affordance-based control seriously! *German Journal of Exercise and Sport Research, 48*(2), 169–175. https://doi.org/10.1007/s12662-018-0506-3

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception, 5*, 437–459.

Lehtonen, E., Havia, V., Kovanen, A., Leminen, M., & Saure, E. (2016). Evaluating bicyclists' risk perception using video clips: Comparison of frequent and infrequent city cyclists. *Transportation Research Part F: Traffic Psychology and Behaviour, 41*, 195–203.

Michaels, C. F., & Oudejans, R. R. (1992). The optics and actions of catching fly balls: Zeroing out optical acceleration. *Ecological Psychology, 4*(4), 199–222.

Postma, D. B., Lemmink, K. A., & Zaal, F. T. (2018). The affordance of catchability in running to intercept fly balls. *Journal of Experimental Psychology: Human Perception and Performance, 44*(9), 1336.

Postma, D. B., Smith, J., Pepping, G. J., Van Andel, S., & Zaal, F. T. (2017). When a fly ball is out of reach: Catchability judgments are not based on optical acceleration cancelation. *Frontiers in Psychology, 8*, 535.

Rock, P. B., Harris, M. G., & Yates, T. (2006). A test of the tau-dot hypothesis of braking control in the real world. *Journal of Experimental Psychology: Human Perception and Performance, 32*(6), 1479.

Rodrigues, S. T., Bertoloni, G. C., Ferracioli, M. C., & Tani, R. A. D. (2006). Controle visual do início e da intensidade da freada em ciclistas: A velocidade não afeta o uso da informação de tempo para colisão. *Brazilian Journal of Motor Behavior, 1*(1), 64–72.

Rodrigues, S. T., Schiavon, R., & Macegoza, J. (2012). O tipo de trajetória não afeta o controle visual da freada em ciclistas. *Revista Brasileira de Educação Física e Esporte, 26*(3), 473–483.

Rogers, S. D., Kadar, E. E., & Costall, A. (2005). Gaze patterns in the visual control of straight-road driving and braking as a function of speed and expertise. *Ecological Psychology, 17*(1), 19–38.

Santana-Cedrés, D., Gomez, L., Alemán-Flores, M., Salgado, A., Esclarín, J., Mazorra, L., & Alvarez, L. (2016). An iterative optimization algorithm for lens distortion correction using two-parameter models. *Image Processing On Line, 6*, 326–364.

Savelsbergh, G. J., Whiting, H. T., & Bootsma, R. J. (1991). Grasping tau. *Journal of Experimental Psychology: Human Perception and Performance, 17*(2), 315.

Seifert, L., Dicks, M., Wittmann, F., & Wolf, P. (2021). The perception of nested affordances: An examination of expert climbers. *Psychology of Sport and Exercise, 52*, Article 101843.

Skrucany, T., Vrabel, J., & Kazimir, P. (2020). The influence of the cargo weight and its position on the braking characteristics of light commercial vehicles. *Open Engineering, 10*, 154–165.

Smith, J., & Pepping, G.-J. (2010). Effects of affordance perception on the initiation and actualization of action. *Ecological Psychology, 22*(2), 119–149.

Stoffregen, T. A. (2000). Affordances and events. *Ecological Psychology, 12*(1), 1–28. https://doi.org/10.1207/S15326969ECO1201_1

Van Der Meer, A. L., Svantesson, M., & Van Der Weel, F. R. (2013). Longitudinal study of looming in infants with high-density EEG. *Developmental Neuroscience, 34*(6), 488–501.

Vansteenkiste, P., Cardon, G., D'Hondt, E., Philippaerts, R., & Lenoir, M. (2013). The visual control of bicycle steering: The effects of speed and path width. *Accident Analysis & Prevention, 51*, 222–227.

Vieira, L. H., Pagnoca, E. A., Milioni, F., Barbieri, R. A., Menezes, R. P., Alvarez, L., … Santiago, P. R. (2017). Tracking futsal players with a wide-angle lens camera: Accuracy analysis of the radial distortion correction based on an improved Hough transform algorithm. *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization, 5*(3), 221–231.

Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10*(5), 683–703.

Winter, D. A. (2009). *Biomechanics and motor control of human movement.* John wiley & sons.

Withagen, R., & Michaels, C. F. (2005). On ecological conceptualizations of perceptual systems and action systems. *Theory & Psychology, 15*(5), 603–620. https://doi.org/10.1177/0959354305057265

Yilmaz, E. H., & Warren, W. H. (1995). Visual control of braking: A test of the r hypothesis. *Journal of Experimental Psychology: Human Perception and Performance, 21*(5), 996–1014.

Zheng, R., de Reus, C., & van der Kamp, J. (2021). Goalkeeping in the soccer penalty kick: The dive is coordinated to the kicker's non-kicking leg placement, irrespective of time constraints. *Human Movement Science, 76*. https://doi.org/10.1016/j.humov.2021.102763

Zheng, R., van der Kamp, J., Song, X., & Savelsbergh, G. (2022). Affordance-based control in deceptive and non-deceptive penalties in soccer goalkeeping: Gender matters! *Psychology of Sport and Exercise, 58*. https://doi.org/10.1016/j.psychsport.2021.102096