

Introduction

To perform everyday behaviours successfully, individuals must perceive which behaviours are and are not possible in any given situation. Opportunities for behaviour (i.e., *affordances*; Gibson, 1979) are emergent relations between the action capabilities of the individual and properties of the environment (Stoffregen, 2003b). For example, an aperture affords crossing for a particular individual based on emergent relations between the individual's shoulder width, balance, and flexibility and the width and composition of the aperture. In this way, Warren & Whang (1987) found that (perception of) the *critical boundary* (i.e., the point of transition) between an aperture that affords crossing with and without rotation of the shoulders could be expressed as a body-scaled aperture-to-shoulder-width ratio of approximately 1.3. More recent studies showed that individuals perceive this affordance relative to the size of the body in motion (Franchak et al., 2012) and adapt their shoulder rotation based on this relationship (Higuchi et al., 2006, 2011; Wilmut & Barnett, 2010). Therefore, (perception of) affordances is likely best captured through action-scaled metrics, and affordances must be actualized in such a way that the behaviour is always within the limit of an individual's (maximal) action capabilities (Fajen, 2007). Therefore, the affordance-based control proposes to study perception and action in relation to the maximal action capabilities (Franchak et al., 2012; Jeschke et al., 2020; Seifert et al., 2021b; Wagman et al., 2019; Zheng et al., 2021, 2022). For example, to cross a lane of traffic without collision, a cyclist must keep the time required to cross the lane below the temporal gap between two passing cars (Chihak et al., 2010). That is, cyclists must pick up reliable information about the time required to cross the lane (i.e., they must be attuned to such information) and establish and maintain the scaling between this information and their action capabilities (i.e., they must calibrate actions to this information) to guide behaviours within the action boundary.

In general, behaviours (and hence affordances) are nested within the larger context of how and why a given behaviour is being performed, including the various means by which that behaviour

can be performed (Stoffregen, 2003a; Wagman et al., 2023). In some cases, the means used to perform the behaviour can change an individual's action capabilities. For example, holding an object or attaching an object to the body —such as sports implements, equipment worn by firefighters or night-vision devices used by the military—can change the perceiving or acting capabilities of the individual (Mangalam et al., 2022). Such objects simultaneously improve perceiving or acting capabilities for some tasks (e.g., the ability to reach distant objects), limit them for other tasks (e.g., the ability to fit through narrow spaces), and create new ones (e.g., the ability to see in the dark).

In particular, when an individual passes through an aperture while holding or wearing an object, the ability to perform this behaviour is constrained by the width of the *person-plus-object system* (Vauclin et al., 2023; Wagman & Taylor, 2005). For example, the critical boundary for crossing an aperture in a wheelchair occurs when the width of the person-plus-object system is slightly larger than the width of the aperture (Higuchi et al., 2004, 2006). Moreover, experience in using an object held by or attached to the body has been shown to improve the calibration of perception and performance of particular behaviours with respect to the action capabilities of the person-plus-object system. For example, experienced wheelchair users more accurately perceived the minimum crossable aperture width than did novice wheelchair users (Higuchi et al., 2009). This was the case regardless of whether participants used their own or wider than usual wheelchairs (Higuchi et al., 2009). Similarly, Higuchi et al. (2011) showed that athletes with experience playing American football exhibited smaller magnitudes and later onset of shoulder rotations when crossing an aperture while wearing shoulder pads than a control group of athletes. It is important to understand how the athlete's level of experience influences perception of affordances, especially when an object attached to the body (such as in cycling) changes both the dimensions of the individual and his or her action capabilities.

Current study

1 The primary objective of this study was to investigate the effect of experience on the
2 perception of affordances for a person-plus-object system in a cycling task. In particular, the aim of
3 our experiment was to investigate whether experience in perceiving and acting with respect to a
4 person-plus-object system (i.e., experience cycling) would influence whether and how a person chose
5 to cross an aperture, especially in relation to the maximal action capabilities. We also explored the
6 emergence of particular action modes in relation to performing this task. To this end, we compared
7 both the probability of decision-making (i.e., the choice of whether or not to cross, regardless of the
8 success of the behaviour) and the probability of performance (i.e., the ability to cross the aperture
9 without touching one of the poles or falling) of experienced and occasional cyclists in an aperture
10 crossing task.

11 First, we investigated whether experienced and occasional cyclists make different decisions
12 about whether to cross an aperture and, whether these groups differ in their tendencies to
13 overestimate or underestimate their ability. Given that affordances may vary between individuals
14 depending on their abilities, decision-making behaviour should be studied in relation to their maximal
15 action capabilities in the task. Therefore, cyclists would be overestimating when they decide to cross
16 an aperture smaller than their maximal action capability (which has the result of hitting the obstacle).
17 We expected that both occasional and experienced cyclists would exhibit successful decision-making
18 (i.e., they would choose to cross apertures that did not exceed their maximal action capabilities) but
19 that experienced cyclists would not necessarily choose to cross apertures that were nearer to their
20 maximal action capabilities than would occasional cyclists (Seifert et al., 2021a).

21 We then investigated whether experienced cyclists exhibited an overall greater ability to cross
22 apertures than occasional cyclists. That is, we investigated (1) whether experienced cyclists would be
23 able to cross apertures at narrower *bike-scaled* aperture widths—the difference between the
24 aperture width and handlebar width— than occasional cyclists and (2) whether experienced cyclists
25 would be able to cross apertures at narrower *action-scaled* aperture widths—the difference between

the aperture width and maximal action capability— than occasional cyclists. Whereas bike-scaled aperture width is entirely *independent* of the action capabilities of the cyclist, action-scale aperture width is entirely *dependent* of the action capabilities of the cyclist. We expected that experienced cyclists will be able to cross narrower bike-scaled aperture widths than occasional cyclists but that experienced cyclists will not be able to cross narrower action-scaled aperture widths than occasional cyclists.

Third, we investigated whether experienced and occasional cyclists choose different modes of action under particular task constraints. In particular, we hypothesized that both experienced and occasional cyclists would choose to cross the aperture with the handlebar straight (i.e., the ‘facing’ mode of action) when the aperture width was larger than the handlebar width, that only experienced cyclists would choose to cross the aperture by rotating the handlebar (i.e., the ‘turning’ mode of action) when the aperture width was below the handlebar width and that experienced and occasional cyclists would dodge the aperture (i.e., the ‘dodging’ mode of action) when they approach their maximal action capabilities.

Method

Participants. A simulation-based power analysis for Generalized Linear Mixed Model (GLMM) (Johnson et al., 2015) was conducted with the *simr* package (Green & Macleod, 2016). Therefore, we built the data and model from scratch following substantiated expectations of the smallest effect size of interest (Kumle et al., 2021). Detailed information about the expected data, the structure of the model, and the code to determine the power analysis is included in the Supplementary Material. The simulation-based power analysis revealed that 8 participants in each group provided more than 80% power to detect an interaction effect of the smallest effect size of interest in task performance. Therefore, we stopped recruitment when the two groups had at least 8 participants after exclusions¹.

¹ An important property of mixed-effects modelling is that it is possible to fit models to unbalanced data sets (Baayen et al., 2008).

Participants were recruited via flyers placed on poster boards within the university. Occasional cyclists were defined as those who cycle for a maximum of 4 hours per week, but within a recreational, not competitive context. Experienced cyclists were defined as those who cycle for at least a mean of 8 hours per week and have experience in cycling competitions. 16 occasional cyclists (8 women, 8 men) and 8 experienced cyclists (8 men) participated in the experiment with a mean age of 23 years (SD = 3 years) and 26 years (SD = 5 years), respectively. All the experienced cyclists had competed in mountain bike competitions, but they were also familiar with road cycling.

All participants reported they were free from any injuries that could adversely affect their performance in the experimental task and provided signed informed consent expressing knowledge of the experimental protocol, which was approved by the Ethics Committee for Sport Science Research in France (IRB00012476-2022-03-01-142) in accordance with the Declaration of Helsinki.

Materials and apparatus. The apparatus and experimental setup are illustrated in Figure 1. The experiment was conducted in a gymnasium split into three zones. A 15 m preparation zone equipped with a light pacing system (*Virtual Swim Trainer, Indico Technologies, Torino, Italy*) on the floor—indicating the speed at which the cyclist was to ride. The preparation zone was followed by a 15 m approach zone. The light pacing system was not installed in the approach zone so as not to interfere with the participant's attention toward the crossing task (both walking and viewing distance affects the detection of visual information; Fath & Fajen, 2011; Higuchi et al., 2006; Wilmut & Barnett, 2010). A 10 m exit zone was also included to allow the participant to safely exit from the aperture. Two PVC pipes (height, 2 m; outer diameter, 50 mm) formed the aperture and were placed between the approach and the exit zones. The pipes are lightweight and flexible and could fall to the ground when touched by the participant both for safety and ethical reasons. Indeed, a previous study showed that pedestrians chose to cross an aperture differently (in terms of the ratio of shoulder to aperture width) when the aperture was between two pedestrians than when it was between two poles (Hackney et al., 2015). A mountain bike (*Megamo Factory*) of size Small or Medium (and a

handlebar width of 72 cm), according to the height of the participant (the choice and adjustment of the saddle was made according to the comfort of the participant and with the help of the experimenter if necessary) was used for the occasional cyclists (Figure 2) while experienced cyclists brought their own mountain bikes (handlebar width: $M = 73.75$ cm, range: 71 – 79 cm), as it was assumed that riding their own bikes would enable experienced riders to perform this task at their maximal action capabilities.

As variation in speed affects affordances for walking through an aperture (Higuchi et al., 2011; Warren & Whang, 1987), speed was checked at the point of aperture crossing by placing photoelectric cells (*Witty, Microgate, Bolzano, Italy*) 2 m before and at the location of the aperture to prevent potential confounding. A target speed of 10 km.h^{-1} was chosen as a comfortable speed for a cyclist to cross an aperture based on a previous studies (Vansteenkiste et al., 2013, 2014) and on a pilot study. Thus, participants were instructed to maintain a 10 km.h^{-1} pace without applying brakes or stopping pedalling. Finally, the participants were only allowed to steer the bike by turning the handlebars and were not allowed to stand up from the saddle. This restricted participants from leaning the bike, but still allowed them to approach the obstacle in their preferred trajectory. Restricting participants to these possibilities allowed us to make to a notational analysis of three different modes of action. As a result, the ‘facing’ mode of action was identified when the participant crossed the aperture with the handlebars straight (Figure 2A), the ‘turning’ mode of action was identified when the participant crossed the aperture with a clear voluntary rotation of the handlebars (Figure 2B and 2C), and the ‘dodging’ mode of action was identified when the participant avoided the obstacle. Modes of action were identified by the experimenter in real-time during data collection, with judgments later confirmed using footage from camera (GoPro Hero10, USA) placed above and beside the obstacle.

Figure 1. The experimental set-up.

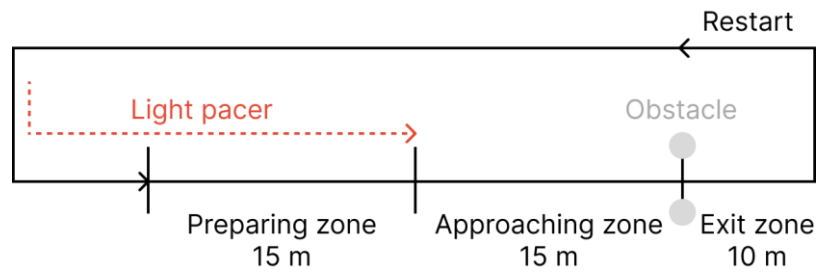


Figure 2. Illustration of action modes for crossing. Figure B and C have been classified in the same action mode 'turning'.

A. 'Facing'



B. Straight approach and 'turning'



C. Curvilinear approach and 'turning'



Procedure. After briefing, participants were asked to adjust the height of the saddle to their preferred position. Afterwards, participants completed a 5-minute habituation period to become accustomed to the mountain bike and the light pacing system.

The experiment required participants to cycle through an aperture in six aperture width conditions (- 2 cm, + 0 cm, + 2 cm, + 4 cm, + 6 cm, + 8 cm relative to handlebar width) for occasional cyclists and seven aperture width conditions (-8 cm, - 6 cm, - 4 cm, -2 cm, + 0 cm, +2 cm, + 4 cm in relative to handlebar width) for experienced cyclists. The different conditions were selected from a pilot study to obtain a range containing at least one aperture width where participants fail 100% of the time and one aperture width where participants succeed 100% of the time. This was done to identify the full range of probabilities (0-100%) for each group. Therefore, different conditions between experienced and occasional cyclists are necessary due to their different maximal action capabilities. Each condition was randomly presented six times for occasional cyclists and five times for experienced cyclists, resulting in a total of 36 trials per occasional cyclists and 35 trials per experienced cyclists collected.

On a given aperture crossing trial, the participants were asked to cross the aperture only if they thought it was possible to do so. They were informed that touching a pole or putting a foot down would be considered a failure. They were required to follow the target speed imposed by a light pacing system in the preparing zone. When entering the approach zone, participants were instructed to maintain their pace until they crossed or dodged the aperture. After each trial, participants were instructed to go back to the starting line and start the next trial. The experimenter stood near the aperture to adjust the width between trials while the participants returned to the starting point.

The maximal action capabilities of the participants were tested after the aperture crossing trials. In this task, participants were instructed to cross even if they thought they could not. Testing started with an aperture width that was 2 cm narrower than the narrowest aperture width that was successfully crossed during the main aperture crossing trials. Participants had two attempts to successfully cross the aperture (i.e., to cross without touching the PVC pipe or putting a foot on the ground). If one of these attempts was successful, the aperture width was decreased by 2 cm; if both attempts were unsuccessful the width was increased by 1 cm. The participant made two more attempts and this process was continued until the smallest crossable aperture width was found for each participant. This smallest crossable aperture width indicated the participant's maximum action capabilities for this task.

Statistical Analysis. All analyses were conducted using R version 4.2.2 (R Core Team, 2022). We built different generalized linear mixed models (GLMMs; *lme4* package; Bates et al., 2015)², each one included aperture width and cycling experience as predictors and participants as a random effect. Aperture widths were scaled to the handlebar width to analyse 'performance scaled to the handlebar' and the action modes and were scaled to the maximum action capabilities to analyse decision making and 'performance scaled to the maximal action capabilities.' Finally, all models had binomial error structures with logit link functions and were fitted with the Laplace approximation (see

² The quality of the GLMM report followed the recommendations of Bono et al. (2021).

Appendix, Table 1). The model was chosen from among the various possibilities (from the simplest to the most complex) on the basis of the *Akaike Information Criterion* corrected for small sample size (AICc) and we ensure the goodness-of-fit of the model by reporting the conditional and marginal coefficient of determination for GLMM (*MuMIn* package; Bartoń, 2022). The main effects in all the models were tested with Wald chi-square test (*car* package; Fox & Weisberg, 2019) with alpha set at .05. Parametric bootstraps with 1,000 iterations determined 95% confidence intervals for the parameter estimation and statistical modelling.

Given that performance and decision making vary probabilistically across repeated trials for the same condition (Franchak & Adolph, 2014), the statistical analysis used allows us to characterise affordances. Researchers usually use the 50% threshold to define the limit of a participant's ability to succeed in a consistent manner and use the slope to determine the level of variability such that steeper slopes indicate more consistency in outcomes and that flatter slopes indicate more variability in outcomes. In particular, steeper slopes indicate that the transition between success and failure occurs over a very narrow range of increments across trials (and participants). Flatter slopes indicate that the transition occurs over a wide range of increments across trials (and participants).

Results

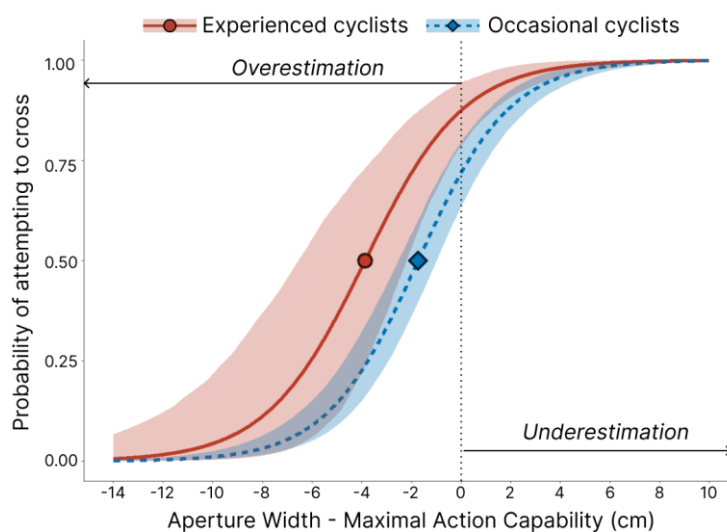
Speed. All trials respected the required speed of 10km/h with an average of 10.1 km/h (SD = 0.5).

Maximal Action Capabilities. Experienced cyclists showed greater maximal action capabilities than occasional cyclists. On average, the experienced cyclists were able to cross bike scaled aperture width of -6.5 cm (SD = 0.9) and the occasional cyclists were able to cross bike scaled aperture width of +1.5 cm (SD = 0.9).

Decision-making. Participants' decisions with respect to whether or not to cross the aperture depended on both action-scaled aperture width and cycling experience. The probability to cross increased with the action-scaled aperture width (condition: $\beta \pm SE = 0.50 \pm 0.12$, 95% CI: 0.31 – 0.87, $\chi^2_1 = 134.372$, $p < 0.001$), and experienced cyclists decided to cross at narrower aperture widths in

relation to their maximal action capabilities compared to occasional cyclists (experience[occasional]: $\beta \pm SE = -1.00 \pm 0.50$, 95%CI: -2.20 – -0.04, $\chi^2_1 = 3.954$, $p = 0.047$). Furthermore, there was no significant interaction between action-scaled aperture width and cycling experience (condition $\times$ experience[occasional]: $\beta \pm SE = 0.04 \pm 0.13$, 95%CI: -0.33 – 0.27, $\chi^2_1 = 0.322$, $p = 0.748$) (*Appendix*, Table 2). Specifically, both experienced and occasional cyclists overestimated their ability to cross the aperture. An examination of the statistical modelling showed that experienced cyclists showed a 50% threshold at -3.87 cm [95% CI: -6.54 – -2.19] and occasional cyclists at -1.73 cm [95% CI: -2.51 – 0.97] (**Figure 3**).

Figure 3. Prediction from the GLMM of aperture crossing decisions as function of cyclist group and action-scaled aperture width. Each line shows the probability of attempting to cross the aperture for experienced and occasional cyclists as a function of aperture width in relation to their maximal action capabilities. In line with Franchak & Adolph (2014), we use a 50% probability of attempting to cross as a threshold to define the narrowest aperture participants perceive as crossable (marked with a circle or a diamond, depending on condition). The 50% threshold occurring at an aperture width narrower or wider than the maximum action capabilities, indicates overestimation and underestimation of ability to cross, respectively. Summary statistics for GLMM are presented in the *Appendix*, Table 2. The shaded areas represent 95% confidence intervals.

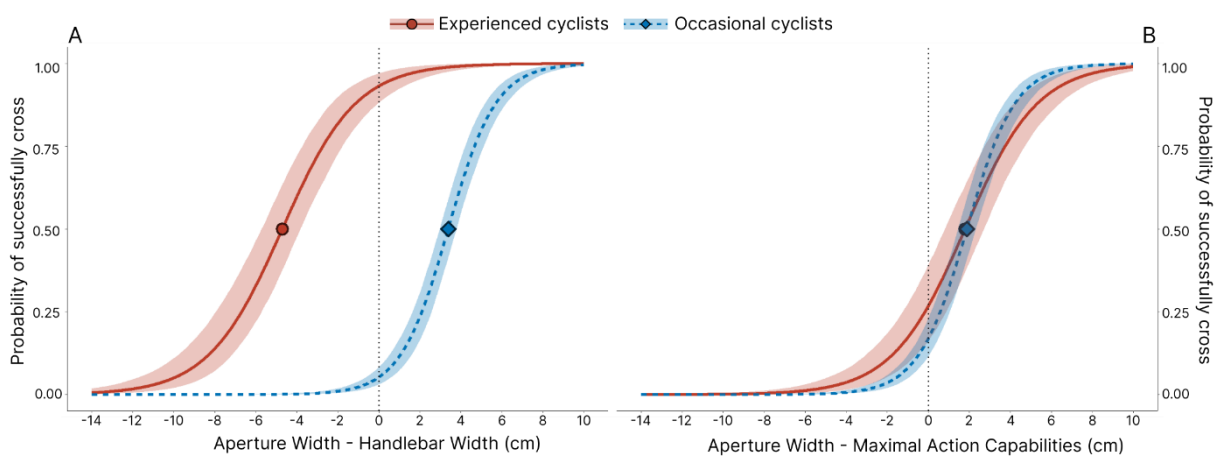


Performance. The ability of participants to successfully cross the aperture depended on both bike-scaled aperture width and cycling experience. The probability of successful aperture crossing increased with the bike-scaled aperture width (condition: $\beta \pm SE = 0.55 \pm 0.07$, 95% CI: 0.44 – 0.72, $\chi^2_1 = 210.79$, $p < 0.001$), and experienced cyclists could cross narrower aperture widths than occasional cyclists (experience[occasional]: $\beta \pm SE = -5.46 \pm 0.52$, 95%CI: -6.67 – -4.58, $\chi^2_1 = 115.84$, $p < 0.001$) (*Appendix*, Table 3). Furthermore, an interaction of bike-scaled aperture width and cycling experience suggested that experienced cyclists were more variable in their performance (condition $\times$ experience[occasional]: $\beta \pm SE = 0.297 \pm 0.09$, 95%CI: 0.10 – 0.50, $\chi^2_1 = 10.20$, $p = 0.001$). An examination of the statistical modelling showed that aperture widths were smaller at a given probability threshold for experienced than for occasional cyclists. Specifically, we observed a difference of 8.1 cm for the 50% threshold (experienced cyclists: -4.7 cm [95%CI: -3.8 – -5.6]; occasional cyclists: 3.4 cm [95%CI: 2.9 – 3.8]) (**Figure 3A**).

When scaled to maximal action capabilities, the ability of participants to cross the aperture depended on action-scaled aperture width but not on cycling experience. The probability of success increased with increased action-scaled aperture width (condition: $\beta \pm SE = 0.56 \pm 0.07$, 95%CI: 0.45 – 0.73, $\chi^2_1 = 208.767$, $p < 0.001$), and there was no significant difference in probability of success between experienced and occasional cyclists (experience[occasional]: $\beta \pm SE = -0.58 \pm 0.45$, 95%CI: -1.48 – 0.24, $\chi^2_1 = 0.13$, $p = 0.91$) (*Appendix*, Table 4). Furthermore, an interaction of action-scaled aperture width and cycling experience suggested that experienced cyclists were more variable in their performance (condition $\times$ experience[occasional]: $\beta \pm SE = 0.28 \pm 0.09$, 95%CI: 0.08 – 0.47, $\chi^2_1 = 9.273$, $p < 0.001$). Specifically, experienced cyclists exhibited equivalent action-scaled aperture at 50% threshold (experienced cyclists: 1.79 cm [95%CI: 0.86 – 2.75], occasional cyclists: 1.88 cm [95%CI: 1.43 – 2.30]) (**Figure 4B**).

Figure 4. Predictions from the GLMM of aperture crossing ability as functions of cyclist group and **(A)** bike-scaled aperture width and **(B)** action-scaled aperture width. Each line shows the probability of

successfully crossing for experienced and occasional cyclists as a function of aperture width. In line with Franchak & Adolph (2014), we use a 50% probability of successfully cross as a threshold to define the narrowest aperture participants is able to cross (marked with a circle or a diamond, depending on condition). For action-scaled aperture width (B), the 50% threshold occurring at an aperture width narrower or wider than the maximum action capabilities, indicates an overperformance and an underperformance. Summary statistics for the GLMMs are presented in Appendix, Table 3 and 4. The shaded areas represent confidence interval set at 95 %.



Action modes. The distributions of each of the action modes— whether *facing*, *turning*, or *dodging*— differed depending on both aperture width and cyclist experience (Figure 5 and Appendix, Table 5-7).

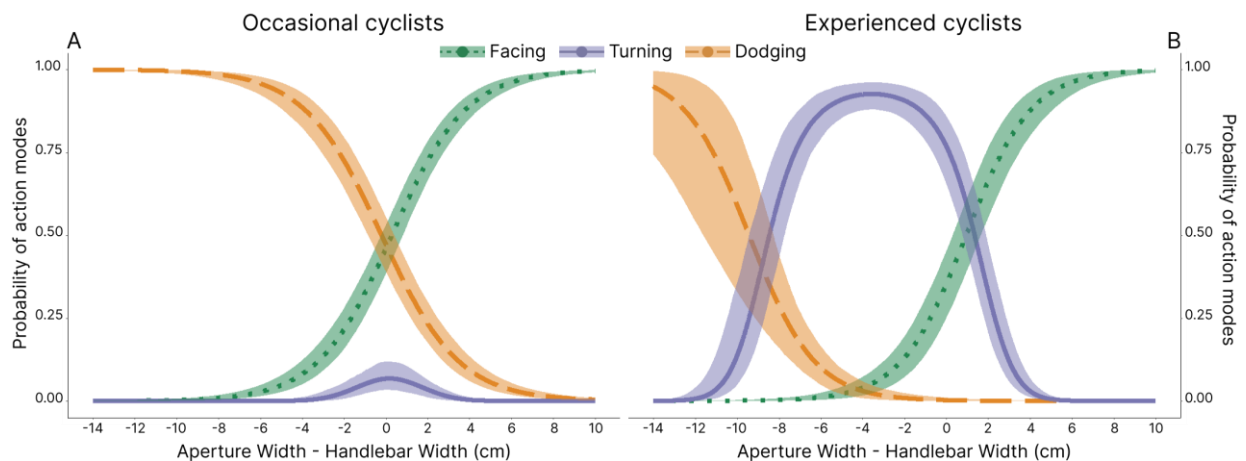
Facing. Participant's choice of crossing with the handlebar straight depended on bike-scaled aperture width but did not vary with cycling experience. The probability of using *facing* action mode increased with bike-scaled aperture width (condition: $\beta \pm SE = 0.64 \pm 0.26$, 95% CI [0.52, 0.83], $\chi^2_1 = 197.15$, $p < 0.001$), and there was no significant difference in the use of the facing action mode between experienced and occasional cyclists (experience[occasional]: $\beta \pm SE = 0.45 \pm 0.31$, 95% CI [-0.17, 1.11], $\chi^2_1 = 1.59$, $p = 0.21$) (Appendix, Table 5).

Turning. Participant's choice of crossing by rotating the handlebar followed an inverted U-shape and depended both on bike-scaled and cycling experience. The probability of using *turning* action mode increased with bike-scaled until it reached its peak at -3.56 cm for experienced cyclists and 0.17 cm

for occasional cyclists (condition: $\beta \pm SE = -178.13 \pm 18.99$, 95% CI [-230.91, -133.44], $\chi^2_1 = 70.87$, $p < 0.001$). A significant interaction of bike-scaled aperture conditions and cyclist experience (condition: $\beta \pm SE = -176.91 \pm 42.86$, 95% CI [.,], $\chi^2_1 = 28.165$, $p < 0.001$) indicated that the difference in use of this action mode between experienced and occasional cyclists was more pronounced below 0 cm (Appendix, Table 6).

Dodging. Participant's choice of going around the aperture depended on bike-scaled aperture width and cycling experience. The probability of using *dodging* action mode decreases with bike-scaled aperture width (condition: $\beta \pm SE = -33.35 \pm 8.03$, 95% CI [-59.37, -26.64], $\chi^2_1 = 133.96$, $p < 0.001$). and experienced cyclists used *dodging* in narrower aperture than occasional cyclists (condition: $\beta \pm SE = 5.89 \pm 1.09$, 95% CI [4.38, 9.88], $\chi^2_1 = 92.92$, $p < 0.001$) (Appendix, Table 7).

Figure 5. Predictions from the GLMM of action modes as function of bike-scaled aperture width among (A) occasional cyclists and (B) experienced cyclists. Each line shows the probability of using one of the three modes of action. Summary statistics for GLMMs are presented in Appendix, Table 6 and 8. The shaded areas represent 95% confidence intervals.



In summary, the use of the *facing* action mode increased with increasing aperture width in the same way for experienced and occasional cyclists. The *turning* action mode was mainly used by the experienced cyclists (at aperture widths smaller than the handlebar widths) while it was nearly

absent among occasional cyclists. The use of the *dodging* action mode decreased with increasing aperture width for both experienced and occasional cyclists but at different rates.

Discussion

The current study investigated whether and how experience in perceiving and acting with respect to a person-plus-object system affects perception of affordances by examining how aperture crossing in cycling relates to experience. Specifically, we investigated whether experience in perceiving and acting in cycling would enhance decision-making (i.e., probability of attempting to cross the aperture) and performance (i.e., probability of success when the cyclist decides to cross) with respect to crossing an aperture, especially in relation to the maximal action capabilities.

In terms of decision making, we expected that experienced and occasional cyclists would both choose to cross apertures that did not exceed their maximal action capabilities and that experienced and occasional cyclists would not exhibit different decision thresholds for crossing. Then, in terms of performance, we expected that experienced cyclists would cross narrower aperture widths (and exhibit greater maximal action capabilities) than occasional cyclists, but that both experienced and occasional cyclists would perform close to their maximal action capabilities (i.e., both groups would exhibit the same degree of calibration to their action capabilities).

We also explored whether the modes of action used by experienced and occasional cyclists varied across aperture widths, and whether these strategies could account for the observed differences in decision-making and performance. We expected that both experienced and occasional cyclists would choose to cross the aperture with the ‘facing’ mode when the aperture width was larger than the handlebar width, that only experienced cyclists would choose to cross the aperture with the ‘turning’ mode of action when the aperture width was below the handlebar width and that experienced and occasional cyclists would use the ‘dodging’ mode of action when they approach their maximal action capabilities.

Overall, the results show that cycling experience partially influences the perception of affordances for aperture crossing. One of the most compelling findings of this study is the overestimation of crossing ability exhibited by both experienced and occasional cyclists. Specifically, this tendency was particularly pronounced for experienced cyclists. In terms of performance, although experienced cyclists had greater ability in the task, they were no more successful performing the task closer to their maximal action capabilities than were occasional cyclists. Finally, to at least some degree, these results can be explained by the ability of experienced cyclists to exploit a wider variety of modes of action which allowed them to successfully cross narrower aperture widths.

Decision-making. Cyclists in this study tended to overestimate their ability to cross the aperture, with a decision error, in relation to their maximal action capability, of approximately -3.87 cm [95% CI: -6.54 – -2.19] for experienced cyclists and -1.73 cm [95% CI: -2.51 – 0.97] for occasional cyclists. This finding is of considerable importance, as errors in judgment made by cyclists on roads or trails could result in injury to themselves and others. Although underestimation is commonly observed in affordance studies, similar results have been observed in firefighters who overestimated their ability to avoid obstacles in simulated firefighting environments (Petrucci et al., 2016; see also Higuchi et al, 2004). More generally, studies have repeatedly shown that the results of estimated action boundaries vary between overestimation and underestimation, which appears to depend on the task and context of estimation. One of the explanations favoured by Ishak et al. (2008) to explain our participant's overestimation may stem from the low penalty associated with errors in tasks such as the one used in the current study (see also Comalli et al., 2013). In our study, the design of the obstacle ensured participant's safety in the event of contact, which may have contributed to overconfidence in their abilities or a greater propensity to take risks. In addition, participants were constrained in their action to cross the aperture, which may have biased their decision in the sense that they may have had higher action capabilities and succeeded in free conditions. Future studies investigating aperture crossing in cycling could be designed to further explore this tendency of

participants to overestimate their ability to cross, firstly, by allowing cyclists to act freely, and secondly, by adding a consequence to the failure of the crossing.

Performance. The analysis of probabilities of successfully crossing apertures revealed that aperture crossing thresholds occurred at an aperture width smaller than the handlebar width (-4.7 cm [95%CI: -3.8 – -5.6]) for experienced cyclists, but larger than the handlebar width (3.4 cm [95%CI: 2.9 – 3.8]) for occasional cyclists. That is, the threshold for aperture crossing occurred at an aperture width narrower than the person-plus-object system for experienced cyclists wider than the person-plus-object system for occasional cyclists. This difference between experienced and occasional cyclists suggests that long term experience in a specific context enhances the ability to effectively actualize affordances within that context (e.g., Higuchi et al., 2011). With respect to the tasks used in the experiment reported here, long term experience in a cycling context enhances the ability of the person to control person-plus-bike-system to cross through an aperture.

The analysis of action modes shows that experienced cyclists exhibited a mode of action (i.e., turning) that was not exhibited by occasional cyclists. As suggested in previous research, this finding appears to relate to the general ability of experienced users of an object attached to the body to incorporate that object into an integrated person-plus-object system. These findings are consistent with those of Higuchi et al. (2011) who showed that athletes with experience in American football were better able to run through an aperture while wearing shoulder pads than were other (control athletes). In particular, the fact that they demonstrated smaller magnitudes and later onset of shoulder rotations than control athletes suggested that experience playing American football served to calibrate these participants to the action capabilities of the person-plus-object system in the context of this task.

Furthermore, the findings showed that both experienced and occasional cyclists effectively perform near their maximal action capabilities when crossing through apertures. As described above, it is likely that experienced cyclists were able to perform near their maximal action capabilities by

exhibiting a more variable and more complex modes of action (i.e., turning) than those exhibited by the occasional cyclists. Thus, our findings are consistent with prior research showing that while task-specific experience enhances a person's ability to perform nested behaviours (Higuchi et al., 2011), it does not necessarily change the relation between such performance and that person's maximal action capabilities (Seifert et al., 2021a).

In addition, the findings showed that performance of the aperture crossing task was more variable for the experienced cyclists than for the occasional cyclists. This result likely stems from the fact that the experienced cyclists used the 'turning mode' far more often than did the occasional cyclists. Presumably, this mode requires more variable coordination relative the facing mode, and this likely resulted in more variable performance. For example, individual were more variable in throwing beanbags than when walking through doorways of different widths (Hospodar et al., 2023).

The current study employed a group design, with separate experienced and occasional cyclist groups. However, there was individual differences in maximum action capabilities even within each group. Future work should replicate the current study using a research design which does not require classification of participants as either experienced or occasional, instead explore the relationship between skill level (reflected by maximum action capabilities) and performance in the aperture crossing task as a continuum.

Action modes. An individual must perceive that an action is possible in a given situation to perform that action under the appropriate laws of control. According to Warren (2006), behaviour arises from the selection of an affordance to be realized (i.e., an intention), which determines the corresponding action mode used to perform that behaviour and the applicable operative laws of control. Therefore, individuals must perceive the critical boundaries between different modes of action in order to perform a given behaviour successfully. For example, the (theoretical) critical point for crossing the aperture when using the action mode of *facing* should occur at a bike-scaled aperture width of 0 cm. For bike-scaled aperture widths less than this, the participant should switch to the

mode of action mode of *turning*. The critical point for crossing the aperture when using the action mode of *turning* should occur at the bike-scaled aperture width representing the individual's maximal action capabilities. For aperture widths narrower than the handlebar width, the participants should switch to *dodging*. In our experiment, we aimed to gather empirical evidence for the selection of action modes by modelling the probabilities of used of these three basic modes of action in relation to the aperture width.

The analysis of action modes provided compelling evidence that experienced cyclists are able to use a wider variety of action modes in crossing an aperture than are occasional cyclists. Specifically, experienced cyclists were more likely to use the *turning* action mode in when passing through bike-scaled aperture widths narrower than 0 cm, while occasional cyclists rarely use this behaviour. In other words, experienced cyclists crossed the aperture by using several action modes—reflecting degeneracy (Edelman & Gally, 2001; Seifert et al., 2016). This does not necessarily imply that occasional cyclists lack the ability to perform this action mode; rather, it indicates that they may not be as likely to perceive affordances for crossing an aperture by this action mode. Therefore, these findings extend previous research by showing that an enhanced action boundary (and maximal action capabilities) is not solely linked to increased action capabilities (Dicks et al., 2010; Higuchi et al., 2011; Navia et al., 2017). Rather, it is also linked to a broader and more accurate (perception of) affordances that in response to changing constraints.

In ecological dynamics, degeneracy—expressed by multi- and meta- stability (Kelso, 2012)—and the ability to exploit it by switching between distinct behaviours in ways appropriate to the specific situation is a hallmark of expertise (Seifert et al., 2013). Indeed, experienced cyclists exhibited the ability to perform different action modes in an aperture crossing task (i.e., facing and turning) whereas occasional cyclists could only use a single action mode — ‘facing’. However, experience might not only result in a larger repertoire of modes of action, but also in an enhanced ability to switch from one mode of action to another depending on the situation. Thus, for successful

performance, the transition between action modes should occur before a given mode becomes impossible. Of particular relevance here is that both experienced and occasional cyclists shift from crossing the aperture to dodging the aperture at an aperture width that exceeds their maximal action capabilities, suggesting both groups overestimate their ability to cross the aperture.

It is hypothesized that skilled behaviour can arise from (1) the emergence of a new action mode in the repertoire or (2) the refinement of the layout of attractors in the landscape of affordances (Bruineberg et al., 2021). Previous research has demonstrated that promoting the metastable region of performance (i.e., a set of possibilities under a constant constellation of task constraints) helps individuals in functionally exploring new behaviours through the exploitation of stable action possibilities and exploring novel possibilities when needed (Orth et al., 2018; Pinder et al., 2012; Seifert et al., 2014). Our results indicated that experience is associated with a richer repertoire of action modes but not better refinement of the landscape (i.e., accurately switching from one mode of action to another) as both experienced and occasional cyclists switch action modes even when the new mode exceeds their maximal action capabilities. Therefore, future research should investigate how the learning environment might promote exploration of the coordination dynamics in cycling to develop the behavioural repertoire and calibrate this landscape. An important limitation of the current study is the restriction to only three possible action modes. This limitation was required to develop an under-constrained task context that entails a continuous behavioural action space. Future work should expand this analysis without restricting cyclists to allow them to fully express their mode of action in relation to the task and measuring variables related to the realisation of particular modes of action (e.g., handlebar rotation angle).

Conclusions

We studied perceiving and acting on affordances for aperture crossing for person-plus-object systems. The aim was to characterize the effect of experience in cycling on decision-making and performance in such a task and to explore whether the distribution of action modes reflects this

1 effect. In term of decision-making, one of the most compelling findings in this study is the
2 overestimation of experienced and occasional cyclists as it could expose cyclists to the risk of a fall or
3 injury on roads or trails. Then, our results indicated that experienced cyclists exhibited an enhanced
4 ability to cross the aperture compared to occasional cyclists but that both groups exhibited
5 comparable ability with respect to maximal action capabilities. Third, modelling of the action modes
6 suggested that these findings are the result of (1) the ability of experienced cyclist to exhibit
7 degeneracy, probably due to a better ability to incorporate the bike into an integrated person-plus-
8 object system and (2) the inaccuracy of the transition between action modes for both groups. Taken
9 together, the present findings may help practitioners design intervention to promote exploratory
10 behaviours for the purpose of enlarge the behavioural repertoire of people developing skilled
11 behaviours.

Appendix

Table A.1. Model specifications

Model	Formula
Decision	$x \sim \text{condition} * \text{experience} + (1 \mid \text{participant})$
Performance	$x \sim \text{condition} * \text{experience} + (1 \mid \text{participant})$
Facing	$x \sim \text{condition} * \text{experience} + (1 \mid \text{participant})$
Turning	$x \sim \text{poly}(\text{condition}, 2) * \text{experience} + (1 \mid \text{participant})$
Dodging	$x \sim \text{condition} * \text{experience} + (1 \mid \text{participant})$

Table A.2: Results of GLMM predicting decision to cross aperture depending on action-scaled aperture width and experience level (experienced, occasional).

Variables	β	95% CI	95% CI	SE	$\chi^2(\text{df})$	<i>p</i> -value
		Lower	Upper			
(Intercept)	1.94	1.15	3.12	0.43		
Condition	0.50	0.31	0.87	0.12	134.372	< 0.001
Experience	-1.00	-2.20	-0.04	0.50	3.954	0.047
Condition × Experience	0.04	-0.33	0.27	0.13	0.104	0.748
R² marg.: 0.74. R² cond.: 0.79.						
Note. CI = confidence interval.						

Table A.3: Results of GLMM predicting crossing performance depending on bike-scaled aperture width and experience level (experienced, occasional).

Variables	β	95% CI Lower	95% CI Upper	SE	$\chi^2(df)$	<i>p</i> -value
(Intercept)	2.61	1.86	3.58	0.41		
Condition	0.55	0.44	0.72	0.07	209.59	< 0.001
Experience	-5.51	-6.67	-4.58	0.52	115.01	< 0.001
Condition × Experience	0.30	0.10	0.50	0.09	10.39	< 0.01
R ² marg.: 0.84. R ² cond.: 0.86.						
<i>Note.</i> CI = confidence interval.						

1

2 **Table A.4:** Results of GLMM predicting crossing performance depending on action-scaled aperture
3 width and experience level (experienced, occasional).

Variables	β	95% CI Lower	95% CI Upper	SE	$\chi^2(df)$	<i>p</i> -value
(Intercept)	-1.01	-1.71	-0.32	0.36		
Condition	0.56	0.45	0.73	0.07	208.767(1)	<0.001
Experience	-0.58	-1.48	0.24	0.45	0.013(1)	0.909
Condition × Experience	0.28	0.08	0.47	0.09	9.2730(1)	<0.01
R ² marg. 0.84. R ² cond. 0.86.						
<i>Note.</i> CI = confidence interval.						

4

5 **Table A.5:** Results of GLMM predicting *facing* action mode depending on bike-scaled aperture width
6 and experience level (experienced, occasional).

Variables	β	95% CI Lower	95% CI Upper	SE	$\chi^2(df)$	<i>p</i> -value
(Intercept)	-0.60	-1.17	-0.13	0.27		
Condition	0.64	0.52	0.83	0.08	197.429(1)	<0.001
Experience	0.45	-0.12	1.12	0.33	1.523(1)	0.217

Condition × Experience	-0.08	-0.28	0.09	0.09	0.736(1)	0.391
R² marg. 0.80. R² cond. 0.82.						

Note. CI = confidence interval.

1

2 **Table A.6:** Results of GLMM predicting *turning* action mode depending on bike-scaled aperture width
3 and experience level (experienced, occasional).

Variables	β	95% CI		SE	$\chi^2(df)$	<i>p</i> -value
		Lower	Upper			
(Intercept)	-6.69	-8.88	-5.09	0.78		
Condition	-379.84	-484.55	-304.64	37.59		
Poly(Condition,2)	-179.61	-232.46	-139.86	19.34	91.201(2)	<0.001
Experience	-6.40	-22.36	-1.56	1.26	51.196(1)	<0.001
Condition × Experience	-62.89	-745.09	153.17	53.45		
Poly(Condition,2) × Experience	-176.91	-706.75	11.59	42.86	28.165(2)	<0.001
R² marg. 0.99. R² cond. 0.99.						

Note. CI = confidence interval.

4

5 **Table A.7:** Results of GLMM predicting *dodging* action mode depending on bike-scaled aperture
6 width and experience level (experienced, occasional).

Variables	β	95% CI Lower	95% CI Upper	SE	$\chi^2(df)$	<i>p</i> -value
(Intercept)	-6.00	-9.68	-4.47	1.07		
Condition	-0.64	-1.11	-0.41	0.15	137.999	<0.001
Experience	5.89	4.37	9.62	1.09	92.912	<0.001

Condition × Experience	0.10	-0.17	0.60	0.16	0.371	0.542
R² marg. 0.80. R² cond. 0.83.						

Note. CI = confidence interval.

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