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Information acquisition differences between experienced and novice time trial cyclists

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Abstract

Purpose: To use eye-tracking technology to directly compare information acquisition behavior of experienced and novice cyclists during a self-paced 10 mile (16.1 km) time-trial. **Method:** Two groups of novice (N=10) and experienced cyclists (N=10) performed a 10-mile self-paced time-trial (TT) on two separate occasions during which a number of feedback variables (speed, distance, power output, cadence, heart rate, and time) were projected within their view. A large RPE scale was also presented next to the projected information and participants. Participants were fitted with a head-mounted eye-tracker and heart rate monitor. **Results:** Experienced cyclists performed both time-trials quicker than novices ($F_{1,18}$=6.8, P=.018) during which they primarily looked at speed (9 of 10 participants) whereas novices primarily looked at distance (6 of 10 participants). Experienced cyclists looked at primary information for longer than novices across the whole time-trial (24.5±4.2% vs. 34.2±6.1%, t_{18}=4.2, P<0.001) and less frequently than novices during the last quarter of the time-trial (49±19 vs. 80±32, t_{18}=-2.6, P=0.009). The most common combination of primary and secondary information looked at by experienced cyclists was speed and distance respectively. Looking at ten different primary-secondary feedback permutations, the novices were less consistent than the experienced cyclists in their information acquisition behavior. **Conclusion**: This study challenges the importance placed on knowledge of the endpoint to pacing in previous models, especially for experienced cyclists for whom distance feedback was looked at secondary to, but in conjunction with, information about speed. Novice cyclists have a greater dependence upon distance feedback, which they look at for shorter and more frequent periods of time than the experienced cyclists. Experienced cyclists are more selective and consistent in attention to feedback during time-trial cycling.

Keywords: Performance; Pacing; Cycling; Vision; Cognition; Decision

Introduction

(Paragraph 1) It is important for athletes to employ their available energy effectively to perform optimally and avoid fatigue during exercise, so that “all energy stores are used before finishing a race, but not so much that a meaningful slowdown occurs.” (8,18,29) Pacing strategy is an essential aspect of competitive prolonged athletic performance and refers to the variation of speed during an event by regulating the rate of energy expenditure (18–21,28). Where completion time is the measure of success, pacing strategy has an influence over success in events lasting longer than 60 seconds (1).

(Paragraph 2) Several factors are known to influence the pacing strategy that an athlete adopts including the duration of the event (8), presence of a competitor (7,57), environmental conditions (41), previous experience (35), perceptions of exertion (49), and the availability and veracity of performance feedback information (14,36). Previous models of pacing place a lot of emphasis on an athlete’s awareness of changes to the internal physiological state of their body, experienced as perceived exertion, in relation to their progress towards the endpoint as informed through various forms of feedback. According to Teleoanticipation Theory (50) and later on the Central Governor Model (40), a ‘central governor’ anticipates exercise and presets a pacing strategy based on the end-point or duration of exercise. In a more recent manifestation of Central Governor Model, more complex information-processing mechanisms have been proposed in which rate of change of perceived exertion is evaluated in the light of expected duration or distance of an event and modified through appropriate alternations in pace (48). The Psychobiological Model similarly supports the notion of effort-related decisions about pace in the context of event duration, but argues that such decisions are entirely conscious and that subconscious processes, such as those proposed by the Central Governor Model, are inapposite (34). The linear relationships found between RPE and the proportion of completed event, are such that the RPE gradient was found to peak in coincidence with the expected endpoint (15,19,31).

(Paragraph 3) In an attempt to factor for varying uncertainty about pace during endurance events, a model has been specified whereby risk is expressed as the proportion of the remaining task multiplied by their momentary RPE, a variable the authors refer to as hazard score (9). An appealing feature of the hazard score model is that the further an athlete progresses, the lower hazard score becomes, thus explaining how athletes are sometimes able to risk performing very intense spurts of energy towards the end of an event when the risk of not-completing as a consequence of doing so is relatively low. An alternative model proposed that pacing decisions are based upon the estimated time that present power output can be maintained, as judged against the duration or length of the task (23). More recent suggestions of how pace is regulated have drawn on the decision-making literature (42) and the interdependence of perception and action in attempting to account for pacing behavior in environmentally complex situations (45).

(Paragraph 4) Whatever theory of pacing is subscribed to, all emphasize knowledge of proximity to the endpoint as a key determinant of pacing strategy. However, the importance placed on endpoint knowledge in pacing models is based on experimental evidence that was collected using limited indirect observation methods where participants have been deceived about, or deprived of, progression or performance feedback information (30). A number of studies have used false feedback about distance or time to understand the importance of feedback and the use of knowledge during exercise. Studies have found that deceiving athletes about the duration of exercise, by providing false or no knowledge about the exercise endpoint, leads to increased RPE and a different pacing strategy caused by an incorrect allocation of physiological resources (3,12). Experience of using blind, true and false performance feedback has also been found to provoke different types of learnt pacing strategies (38).

(Paragraph 5) Feedback deception and blinding experimental methods have been the dominant approaches used to understand how athletes use information to pace themselves. Deductions about the significance and role of particular types of performance information are made based upon what happens to pace if that information is altered or removed. The underlying logic is that if, after altering or removing a particular source of information pacing or performance worsens, then it can be inferred that that information source has an important contributory role. It has been this approach that has led to the emphasis placed on knowledge of the endpoint in various pacing models.

(Paragraph 6) There are several limitations to this information-knockout approach. The first is the focus on singular sources of information and the lack of investigative sophistication in understanding how athletes interpret various sources of information in conjunction with each other. For example, the importance athletes place on speed or power information to make pacing decisions could potentially vary according to how much time or distance has elapsed, or according to environmental conditions or competitor behavior. A further, but related, limitation is that knockout and deception studies have not investigated within-trial changes in the emphasis placed on certain types of feedback. For example, potentially an athlete may be more concerned with average speed in the first half of a race and then become more interested in elapsed time or distance towards the end of an event. The final limitation is the inability to understand individual differences in feedback preferences, which could vary according to past experience or the outcome measure by which they appraise their achievement success. A threat to the validity of previous pacing models is the reliance on limited deception and blinding methods, which necessitated indirect interpretation regarding the importance of endpoint awareness as a determinant of athletic pace. It is this point that the present study intended to redress.

(Paragraph 7) A more direct method of measuring what information athletes seek and use during self-paced exercise will greatly improve our understanding of pacing decisions and, to our knowledge, this have never been achieved. In one study the frequency with which children looked at elapsed time during a time-limited run was measured from a video recording and it was found that they looked at the watch more often towards the end of the run (6). While the methods of measuring information acquisition in this study were quite basic, eye-tracking technology does provide a more sophisticated method of directly measuring what information athletes look at during self-paced exercise. Unlike previous deception and information-knockout studies, the precision with which information acquisition behavior can be measured using eye-tracking technology is able to overcome the limitations of deception studies discussed earlier. Importantly, eye-tracking enables detailed information to be gathered about how athletes acquire information in dynamic and conjunctive ways during an exercise trial, as well as how they learn to use information differently with experience to pace themselves.

(Paragraph 8) The use of eye-tracking technology in sport is a powerful method (11) that has enabled researchers to develop better insights about perceptual-cognitive mechanisms of sport performance (24, 33). Mobile eye-tracking technology has proven especially versatile in allowing researchers to collect data in many different sports domains where performance is dependent upon the ability perceive and process complex information in often fast moving environments. In such situations, the visual is the dominant mode of sensory feedback in the perceptual-action coupling (32), a system in which attention to external cues enables the kind of adaptive movements required for the successful performance of motor tasks such as catching or striking a ball. In the context of cycling, eye-tracking has provided useful insights about the role of visual behaviour in balance and steering (51, 53) but has not been used to understand information pick-up as part of the perceptual-action processes in regulating pace (45). Eye-tracking technology has also provided considerable insights about differences in perceptual-cognitive mechanisms between expert and novice performers (24, 55), and this approach has great potential in developing a better understanding of information acquisition and decision-making during self-paced cycling. Generally, previous research has suggested that experts across many sports domains tend to look at task-relevant information less frequently and for less time than novices (24,27). This has a relevance to pacing theory because it raises the question of whether differences exist between expert and novice cyclists about what information feedback they consider to be task relevant, and whether differences exist in how frequently they refer to such information and for how long.

(Paragraph 9) While we acknowledge that the use of eye-tracking technology is fairly common-place in sport domains and expertise research, the present study used eye-tracking technology in an original way to better understand information acquisition and pacing behaviour in cyclists. The purpose was, for the first time, to directly measure what information cyclists look at while performing a time-trial, and to compare the information-acquisition strategies of novice and experienced cyclists. We hypothesized that experienced cyclists would look at fewer sources of information, and would seek out information less frequently compared to novices.

Methods

Participants

(Paragraph 10) Experienced (n=10) and novice male cyclists (n=10) were recruited for this study from the University of Essex and local cycling clubs. Mean ± 1SD age, stature and body mass for the experienced cyclists was 38.6 ± 11.3 years, 176.6 ± 6.9 cm and 74 ± 9.4 kg for the experienced cyclists, and for the novice cyclists was 36.1 ± 9.9 years, 178.5 ± 6.7 cm and 80.2 ± 8.7 kg. The experienced cyclists were recruited from local cycling clubs and had participated in competitive 16.1 km time-trials for an average of 14.1 ± 13 years. During the 6 months preceding the study, the experienced cyclists had on average trained each week on 4.7 ± 1.1 occasions for a total of 8.5 ± 2.1 hours. The novice cyclists were recruited from the University of Essex staff and students and, although they could all ride a bicycle, they had never trained for, or participated in competitive cycling events of any kind. In an attempt to control for fitness, only physically active individuals were recruited to the novice group who had on average trained each week on 2.8 ± 0.8 occasions for a total of 4.6 ± 1.1 hours across a range of different sports that did not involve cycling. Each participant provided written informed consent to take part in this study, which was approved by the University of Essex ethics committee.

Design

(Paragraph 11) A two-way mixed experimental design (experience-by-segment) was used in which we compared pace, performance and visual information acquisition between novice and experienced cyclists (between-subjects experience factor) during a 16.1 km cycling time-trial every 4 km (within-subjects segment factor). All participants performed a 16.1 km familiarization time trial (TT_{FAM}) and then had a recovery period of 5 to 10 days before completing the 16.1 km experimental time-trial (TT_{EXP}). During each time-trial completion time (s), speed ($km.hr^{-1}$), power output (W), distance (km), pedaling cadence ($r.min^{-1}$) and heart rate ($b.min^{-1}$) was measured. RPE was recorded every 4 km. Participants wore a monocular eye-tracking device for familiarization purposes during TT_{FAM} and then to measure the type, duration and frequency of information they looked at during TT_{EXP}.

Procedure

(Paragraph 12) Before each time-trial participants were asked to refrain from ingesting caffeine for at least 6 hours, alcohol for 24 hours and food for 2 hours prior to testing. Participants were also asked not to train or engage in heavy physical work for 24 hours before testing. On the first laboratory attendance each participant had their body mass and stature measured and was briefed as to the requirements of the trial but not the purpose of the study. Participants also completed a short training history questionnaire. After all tests had been completed, participants were debriefed about the purpose of the study.

Cycling Ergometry and Video Simulation

(Paragraph 13) All cycling tests were performed on a Velotron (3D) Racer Mate ergometer with RealVideo simulation software (Racermate, Seattle). The 16.1 km time-trial duration was selected as this is a common format used in the UK and one which the experienced cyclists used in this study were most accustomed. All cycling tests were performed at the same time of day ± one hour to control for circadian variation in outcome measures. Prior to each time-trial, participants performed a standardized 5-minute self-paced warm-up. Participants were instructed to complete the time-trial in the fastest possible time. They were not provided with any information acquisition or pacing guidance.

(Paragraph 14) During each time-trial, a RealVideo simulated cycling course was projected onto a wall in front of and slightly offset to the right of the cycling. The projected video footage was coupled in a multiplicative way to the cyclists' actual power output such that any alteration in speed was instantly represented on the screen. Notwithstanding minor projector repositioning variances, the projected screen size was 2.1 m wide by 1.5 m high with the bottom border of the projection running 1 m above and parallel to the floor. The cycle ergometer was positioned such that the handlebar stem riser was 3 m perpendicular to the plane of the screen which itself was offset to the right of the natural forward field of vision of the cyclists with a vector displacement of 8° at 3.03 m for the left border of the projection and 40° at 3.91 m for the right border (visual arc 32°). Offsetting the screen in this way required participants to rotate their neck to look at the projected information, thus adding confidence that the eye-tracking measurements constituted deliberate attempts to acquire information, rather than information glances just because it happened to fall naturally within participants forward field of vision.

(Paragraph 15) Incorporated into the projection beneath the simulated time-trial video, were five fields of real-time feedback information which, presented from left to right, were speed (km.hr^{-1}), elapsed distance (km), power output (W), pedaling cadence (r.min^{-1}) and heart rate (b.min^{-1}). The row of five feedback information fields were 0.375 m above and parallel to the bottom border of the projection or 1.375 m above the floor. The vector displacement of the center of each information field from the handlebar stem riser was speed (9.5°, 3.04 m), elapsed distance (18.1°, 3.16 m), power output (26.0°, 3.34 m), pedaling cadence (32.9°, 3.57 m) and heart rate (38.9°, 3.86 m). Elapsed time (min:sec) was displayed above the heart rate field (3.0°, 0.2 m). The block size of individual characters within each field was 4.5 cm high by 2.9 cm wide. Angular separation of the information fields was at its most acute 3° (elapsed time – heart rate) and at its least acute 8.6° (elapsed distance - speed), well beyond the manufacturer-defined eye-tracker spatial resolution of 0.1˚ and gaze position accuracy within the nearest degree. The size and separation of the projected information blocks therefore facilitated clear differentiation in eye-tracker measurements as later described. An A0 sized RPE scale was also displayed to the left of the projector screen.

Psychophysiological Measures

(Paragraph 16) Heart rate (HR) was recorded during both cycling time-trials every (120) milliseconds using a chest strap Polar Accurex Plus heart rate monitor (Polar Electro. Kempele, Finland) connected via wireless to the Velotron software. Average HR was calculated every 4 km. Participants were asked to provide an overall rating of perceived exertion every 4 km using the Borg 6-10 RPE scale (5). All subjects were familiarised with the RPE scale, which was administered in accordance with published standardised instructions (4).

Eye-Tracking and Video Analysis

(Paragraph 17) Participants were fitted with a SensoMotoric Instruments SMI iViewX head-mounted monocular eye-tracking device (HED). The system consists of two cameras mounted on a cycling helmet, one that records the eye position of the participant, and a 3.6 mm wide-angle forward-looking camera that records the scene the participant is looking at. Eye position was recorded at 50 Hz, which was then down-sampled to 25 frames per second for the resulting scene videos. The eye-tracker was calibrated using the participant's left eye in accordance with the manufacturer's instructions by asking participants to fixate a series of markers spanning the area of the display. Calibration accuracy was checked sporadically and at the end of the time trial by asking the participant to fixate points on the screen and information display. The equipment has a manufacturer-defined spatial resolution of 0.1° and tests demonstrated that gaze position was accurate to within the nearest degree. The system tracks eye movements using pupil and corneal reflex so that each participant's point of regard can be superimposed onto the recorded scene, thus enabling timed measurements to be made of eye fixations.

(Paragraph 18) The eye-tracking videos for TT_{EXP} were subsequently reviewed and manually coded by the first author. Manual coding of eye-tracking data remains the state-of-the-art in active tasks, (52) and within-coder comparisons indicated that gaze location could be determined unambiguously. Reliability of similar methods have shown very good inter-rater reliability (22). Due to the relatively low sampling rate of the eye-tracker, saccades could not be automatically detected, but fixations were only coded when data was within the same region for at least 3 frames (≅ 100 ms). Eye gaze was coded by recording the start and end frame of each entry into a new region of interest. This allowed us to determine the periods of time spent inspecting each of then eye fixation times were manually recorded in milliseconds against nine predetermined categories. Six of the categories related to information feedback that were speed, elapsed distance, power output, cadence, heart rate and elapsed time. Eye fixation times were also recorded for the rating of perceived exertion and the video simulation of the time-trial course that was projected onto the wall. A final category was created to capture all other objects of regard not corresponding to the other eight categories, for example, when participants looked at the laboratory floor or at laboratory equipment. Fixations of less than 3 frames, blinks and other periods of data loss (e.g. when participants looked at extreme angles) were also included in the 'other' coding category. This procedure allowed detailed coding of point of regard for the whole length of the time trial.

Data Processing and Statistical Analysis

(Paragraph 19) Total gaze time and gaze frequency for each of the nine categories (speed, elapsed distance, power output, cadence, heart rate, elapsed time, video simulation and other) was calculated on a participant-by-participant basis for the whole time-trial and for each 4 km segment. Gaze frequency, defined as the number of separate eye fixations for each category, and total gaze time, defined as the accumulated time of all eye fixations for each category, were calculated for each participant across the whole time-trial and for each segment. Total gaze times were then used to determine what information source that each participant looked at for longest accumulated average time (primary), second longest accumulated average time (secondary), third longest accumulated average time (tertiary) and so on until quaternary (4th), quinary (5th), senary (6th), septenary (7th), octonary (8th) and nonary (9th) had all been established. To normalize absolute total gaze times for inter-participant differences in time-trial performance, primary to nonary fixation data were all converted from absolute time (ms) to percentage of time-trial completion time.

(Paragraph 20) Time-trial average cycling speed (performance) interactions between experienced and novice cyclists, and between the first and second time-trials was analysed using two-way mixed ANOVAs. Three-way mixed ANOVAs were used to analyse group-by-trial-by-segment interactions in average cycling speed (pace) as well as relative fixation time and gaze frequency for the primary, secondary and tertiary visual categories.

(Paragraph 21) For both performance, pace and visual data, significant interactions were followed up using planned post-hoc comparisons between segments using paired-samples *t* tests for within-group comparisons and independent sample *t* tests for between-group comparisons. Paired-samples *t* tests were also used to compare within group comparison and RPE values. All results are expressed as mean (SD) and effect sizes as partial eta squared.

Results

Time Trial Performance, Heart Rate and RPE

(Paragraph 22) Two-way mixed ANOVAs revealed the following experience and trial factor outcomes. Average cycling speed: No group-by-trial interaction ($F_{1,18}$=2.7, P=.082, η_p^2=.16) but there was a group main effect ($F_{1,18}$=6.8, P=.018, η_p^2=.27) and a trial main effect ($F_{1,18}$=11.2, P=.004, η_p^2=.38). Completion time: No group-by-trial interaction ($F_{1,18}$=2.7, P=.082, η_p^2=.16) but there was a group main effect ($F_{1,18}$=6.8, P=.018, η_p^2=.27) and a trial main effect ($F_{1,18}$=11.2, P=.004, η_p^2=.38). Average power output: No group-by-trial interaction ($F_{1,18}$=0.6, P=.440, η_p^2=.03) but there was a group main effect ($F_{1,18}$=10.8, P=.004, η_p^2=.38) and a trial main effect ($F_{1,18}$=11.6, P=.003, η_p^2=.39). Average pedaling cadence: No group-by-trial interaction ($F_{1,18}$=0.1, P=.740, η_p^2<.01) or trial main effect ($F_{1,18}$=3.6, P=.07, η_p^2=.17) but there was a group main effect ($F_{1,18}$=12.7, P=.002, η_p^2=.414). Average heart rate: No group-by-trial interaction ($F_{1,18}$=0.3, P=.086, η_p^2<.01), no group main effect ($F_{1,18}$<0.1, P=.945, η_p^2<.01) and no trial main effect ($F_{1,18}$=0.2, P=.646, η_p^2=.01). Average RPE: No group-by-trial interaction ($F_{1,18}$<0.1, P=.929, η_p^2<.01), no group main effect ($F_{1,18}$=0.4, P=.518, η_p^2=.02) and no trial main effect ($F_{1,18}$=0.9, P=.361, η_p^2=.05). Group and trial differences in performance, heart rate and RPE variables are presented in Figure 1A, with post-hoc statistical outcomes indicated for significant differences between novice and experienced cyclists (independent samples t-tests) and between familiarization and experimental time-trials (paired samples t-tests).

Segment Comparisons of Performance, Heart Rate and RPE

(Paragraph 23) There were no group-by-trial-by-segment interactions or two-way interactions for speed, completion time, power, cadence, heart rate or RPE. Trial main effects were found for speed ($F_{1,18}$=12.9, P=0.002, η_p^2=.42), completion time ($F_{1,18}$=12.9, P=0.002, η_p^2=.42) and power ($F_{1,18}$=11.5, P=0.003, η_p^2=.39). Segment main effects were found for speed ($F_{3,54}$=4.3, P=0.009, η_p^2=.19), completion time ($F_{3,54}$=4.3, P=0.009, η_p^2=.19), power ($F_{3,54}$=6.9, P=0.001, η_p^2=.28), heart rate ($F_{3,54}$=101, P<0.001, η_p^2=.85) and RPE ($F_{3,54}$=518, P<0.001, η_p^2=.97). Group main effects were found for speed ($F_{1,18}$=7.9, P=0.012, η_p^2=.31), completion time ($F_{1,18}$=7.9, P=0.012, η_p^2=.31), power ($F_{1,18}$=10.8, P=0.004, η_p^2=.38) and cadence ($F_{1,18}$=12.7, P=0.002, η_p^2=.414). Post hoc independent samples t-tests found experienced cyclists were faster than novices during every time-trial segment, in both TT_{FAM} and TT_{EXP}. Group and segment differences in pace with post-hoc outcomes are presented in Figure 1B for TT_{FAM} and in Figure 1C for TT_{EXP}. Mean and standard deviation data for speed, completion time, power, cadence, heart rate and RPE are given in Table 1 for each group, time-trial and segment along with post hoc statistical test outcomes.

Whole Time-Trial Eye-Tracking Outcomes: Total Gaze Duration and Gaze Frequency

(Paragraph 24) Novice and Experienced mean total gaze duration data for primary through to nonary points of regard were calculated over the full 16.1 km for TT_{EXP} and are presented in Figure 2A. A two-way mixed ANOVA found a group-by-point of regard interaction for total gaze duration (% time-trial duration), $F_{8,144}$=10.9, P<0.001, η_p^2=.38. Independent-samples post-hoc t-tests revealed that experienced cyclists looked at primary points of regard for longer than novices during TT_{EXP} (34.2 ± 6.1% vs. 24.5±4.2%, t_{18}=-4.2, P<0.001, η^2=0.49). Other experienced vs. novice post-hoc outcomes for total gaze time are represented in Figure 2A.

(Paragraph 25) The frequency of which novice and experienced participants looked at primary through to nonary points of regard was counted overall for TT_{EXP} and is presented in Figure 2B. A two-way mixed ANOVA found a group-by-point of regard interaction for gaze frequency, $F_{8,144}$=2.2, P=0.03, η_p^2=0.11. Independent-samples post-hoc t-tests revealed that experienced cyclists looked at information less frequently than novices (Figure 2B).

Time-Trial Segment Eye-Tracking Outcomes: Total Gaze Duration and Frequency

(Paragraph 26) Segment changes in gaze duration and gaze frequency were analysed using two-way mixed ANOVAs for primary, secondary and tertiary points of regard. Group main effects were found for total gaze duration for the primary point of regard ($F_{1,18}$=16, P<0.001, η_P^2=0.47) and the secondary point of regard ($F_{1,18}$=6.7, P=0.02, η_P^2=0.27) but not the tertiary point of regard. No segment main effects or segment-by-group interactions were found for primary, secondary or tertiary points of regard (Figures 3A-C). For gaze frequency of the primary point of regard a segment-by-group interaction was found ($F_{3,54}$=3.4, P=0.02, η_P^2=0.16) and a segment main effect ($F_{3,54}$=2.8, P=0.05, η_P^2=0.13) but not a group main effect. For gaze frequency of the secondary point of regard only a group main effect was found ($F_{1,18}$=8.9, P=0.008, η_P^2=0.33) with no segment main effect or segment-by-group main effect. There were no gaze frequency interactions or main effects for the tertiary point of regard (Figures 4A-C).

(Paragraph 27) Group-by-trial-by-segment analysis for quaternary through to nonary points of regard are excluded from this article for the sake of brevity, owing to the large amount of statistical data. We also believe that the analysis of gaze data beyond the three most looked at points of regard are unlikely to yield significant insights about systematic perceptual patterns, pacing and performance.

Primary-Secondary Point of Regard Combinations

(Paragraph 28) Data is presented in Table 2 shows the combination of primary and secondary points of regard that participants looked at across the entire experimental time-trial and on a segment-by-segment basis. Individual participant data is present in an attempt to convey the complex, yet in some instances similar, patterns of information that participants looked at during the time-trial. Seven primary-secondary point of regard combinations were observed for the novice group during TT_{EXP}, whereas the experienced cyclists exhibited only three primary-secondary point of regard combinations.

(Paragraph 29) Mann-Whitney non-parametric comparisons were made between novices and experienced cyclists in the number of primary points of regard they looked at in each segment and the number of times they switched what they primarily looked at between segments. Results showed a lower number of different primary points of regard by experienced cyclists compared to novices during TT_{EXP}

(1.7±0.8 vs. 2.8±0.9, U=19.5, Z=-2.41, P=0.008). From segment to segment, the number of times participants switched to a different primary point of regard was lower among the experienced cyclists compared to novices (1.3±1.4 vs. 2.3±0.9, U=31, Z=-1.53, P=0.064). Primary point of regard and switch data is given in Table 2.

(Paragraph 30) A two-way mixed ANOVA found a group-by-segment interaction for the percent dominance of the primary point of regard in the primary-secondary combination, $F_{3,54}$=4.4, P=0.05, η_p^2=.20, a group main effect, $F_{1,18}$=9.4, P=0.007, η_p^2=.34, but no segment main effect, $F_{3,54}$=0.4, P=0.52, η_p^2=.02. Independent-samples post-hoc t-tests revealed that dominance of the primary point of regard in the primary-secondary combination was greater among experienced cyclists compared to novices for the 0-4 km segment (63.8±7.8% vs. 53.6±3.2%, t_{18}=-3.8, P<0.001, η^2=0.45), the 4-8 km segment (61.7±8.0% vs. 56.2±4.3%, t_{18}=-1.9, P=0.036, η^2=0.17), the 8-12 km segment (63.4±6.5% vs. 56.6±5.3%, t_{18}=-2.6, P=0.01, η^2=0.27) but not the final 12-16.1 km segment (59.8±7.6% vs. 60.1±7.8%, t_{18}=0.1, P=0.93, η^2<0.01). Group-by-trial-by-segment primary dominance values are given in Table 2.

Discussion

(Paragraph 31) This study was the first to make direct measurements of information-acquisition behavior among time-trial cyclists and constitutes a significant step forward in our understanding of endurance exercise pacing mechanisms. It seems that patterns of information acquisition during a self-paced cycling time trials are very complex and that pacing behavior is not necessarily universally informed by the integration of endpoint awareness and perceived exertion, as previous models have argued (9,15,20,23,40,46,48,50). This is because we observed that, firstly, cyclists refer to different types of information according to their experience, with experienced cyclists primarily looking at speed and novices primarily looking at distance (Fig 2A). Secondly, experienced cyclists appear to be more selective in their information acquisition behavior compared to novices, referring to fewer sources of information, which they look at for longer (Fig 2A) and less frequently (Fig 2B). Thirdly, novices increased the duration (Fig 3A) and frequency (Fig 4A) of looking at their primary information source during the final segment of the time-trial but experienced cyclists were more constant throughout the trials. Finally, with only four different combinations of primary and secondary information used by the experienced cyclists, there was better commonality in what information they looked at compared to the novices who used seven primary-secondary information combinations (Table 2). Our finding that experienced cyclists refer to task-relevant information less often is consistent with a meta-analysis of eye-tracking studies of expert performers (24), yet our findings that experienced cyclists fixate for longer than novices is not consistent with the meta-analysis (24). This maybe because, as acknowledged by the authors of the meta-analysis, the type of sport task may moderate expert-novice differences in visual behavior compared to other domains (24). Experienced cyclists also tended to stick to a primary information source throughout the time-trial, whereas novices switched the type of information they primarily looked at between segments much more often (Table 2). We are not suggesting that endpoint awareness is not important in pacing regulation, clearly it is given how often it featured as either a primary or secondary point of regard in our findings (Table 2). Our argument is that previous pacing models are deficient in accounting for variations in information acquisition that we have found attributable to individual preference, expertise or event segment. It seems that in simulated time-trial cycling experienced cyclists look at speed more than distance, whereas distance feedback appears to be what novices seek out more.

(Paragraph 32) An important finding of this study was that experienced and novice cyclists differed in the types of information they looked at during the experimental time trial. The majority of the experienced cyclists (9 of 10 participants) tended to look at speed most across the whole time trial. In contrast most novices (6 of 10 participants) looked at distance most, noting that a significant number of novices (4 of 10 participants) chose to primarily look at other information too. In addition to experienced cyclists being more consistent in what information they look at, of note is that they looked at primary information for longer and less frequently.

(Paragraph 33) While the eye-tracking data we have collected reveals a lot about how time-trial cyclists acquire information, it does not tell us anything about how the information is integrated and processed, or the decisions they have made. For this, other process-tracing methods such as think aloud protocols, may usefully compliment eye-tracking in the study of decision-making and pacing. This is because that, while eye-tracking technology provides a powerful method for measure information acquisition processes, it reveals nothing about how that information is subsequently processed. Although longer eye fixation times have been linked to greater depth of processing (16,26,43,44), rather than assuming this to be the case in future pacing studies, it would be preferable to use eye-tracking in conjunction with think aloud protocols to directly capture information processes. Nevertheless, the results of the present study so highlight differences in information acquisition between novice and experienced time-trial cyclists that bring to question the common information-processing mechanisms put forward by previous pacing models (9,15,18,23,31,34,40,42,45,50). In particular, the assumption in previous pacing models that the integration of endpoint awareness with perceived exertion is the primary and universal driver of pacing decisions, regardless of athletic experience or individual feedback preferences. It may be that decision-making among experienced cyclists was different to novices and indeed different between individuals which resulted in a need to seek out more varied sources of information. This is consistent with the idea that individuals use information in an adaptive way according to the perceived demands of a situation or problem (25). Thus, it could be that distance information is still important to experienced cyclists but, owing to their previous experience, they are able to process and integrate such information much more quickly and thus do not need to look at it quite so often or for so long. Since the experienced participants were experienced at performing the 16.1 km time-trial format, it is also quite likely that their need to refer to distance information was less than novices unaccustomed to cycling such a distance. The extent to which information acquisition differences between experienced and novice cyclists are attributable to distance familiarity, is something that could be tested by using the same experimental protocol but with an unfamiliar time trial distance. While it is well established that experience influences pacing strategy (19,35,38), our findings further show that information acquisition strategies accompanying pacing behavior also vary with previous experience.

(Paragraph 34) As expected the experienced cyclists completed both time-trials faster than the novices, with both groups exhibiting a mostly constant pace throughout. Owing to imperfect fitness matching between the novice and experienced cyclists, we cannot conclude that that time-trial performance differences between the groups was exclusively due to experience differences. While in future studies greater effort should be made to measure associations between moment-by-moment change in gaze and pacing time-series data (37), in this study we have limited our analysis to detecting concomitant changes in gaze and pace at a segment-by-segment level. What our data clearly shows is that, whatever type of information is preferred as the primary reference, the experienced cyclists looked at it for longer than the novices but less frequently. As previously discussed, this is broadly consistent with previous expertise literature (24). During the second time-trial the experienced cyclists increased the relative amount of time they spent looking at the primary information source from 30 to 35% showing that they became more selective in what information they referred to. The shallower curves presented in Figure 2A also shows that novices tended to distribute their attention across a number of different information sources, spending more time looking at quaternary to octonary sources of information compared to the experienced cyclists. The notion that experienced cyclists are more selective in what feedback they look at is also consistent with previous expertise literature (24,33) and is supported in a number of ways. In the first three segments, the experienced cyclists on average spent between 5-10% longer than novices looking at the primary point of regard. It was only in the last segment of the time-trials from 12-16.1 km, that the novices increase both the amount of time and the frequency with which they look at the primary information source close to that of the experienced cyclists. The increased information acquisition behavior towards the end of the time-trial is consistent with the behavior observed in children during a self-paced running task (6), further supporting the idea that feedback-dependency is more strongly associated with proximity to the end-point among inexperienced athletes compared to experienced athletes.

(Paragraph 35) The data from our study indicates greater consistency in experienced cyclists' approach to information acquisition both in terms in inter- and intra-participant behavior. Inter-participant consistency is evident in the data showing that 9 of 10 experienced cyclists chose to primarily look at speed. Even when combinations of information sources are considered, experienced cyclists consistency chose either speed-distance (5/10), speed-other (2/10) or speed-power (2/10) as the combination of primary and secondary points of regard. In fact, the experienced cyclists only exhibited four different primary-secondary information combinations, whereas seven different primary-secondary combinations were observed among the novices (Table 2).

(Paragraph 36) Greater intra-participant consistency among the experienced cyclists is apparent owing to the fact that on a segment-by-segment basis, the modal primary-secondary combinations were speed-distance and speed other, but for the novices it was often not possible to specify a modal combination because the primary-secondary permutations were so varied. On average novices used 2.3 different primary information sources across the four segments compared to 1.5 for the experienced cyclists. Novices also tended to switch primary information sources between segments more frequently than the experienced cyclists as indicated in Table 2.

(Paragraph 37) The primary-secondary combination data presented in Table 2 is also interesting because it highlights that distance is still an important reference source to experienced cyclists, but only secondary to and in combination with speed. In contrast, distance feedback appears to be the most dominant type of information they refer to in combination with many other types of secondary information. A lot of emphasis has been placed the role of the endpoint in influencing pacing (2,3,9,15,19,31,34,40,46,50) support for which being found in a number of studies where deception or blinding methods have been used (3,12,30,38). However, our study shows that the importance placed on knowledge of the end-point may be overstated in most pacing models and that, knowledge of the endpoint may in fact be a secondary to information about speed in informing the actions of experienced cyclists. Another interesting outcome of this study is that perceived exertion did not feature in the primary-secondary information acquisition combinations for any of the participants (Table 2), and that, whether experienced or novice cyclists, all looked at least three other sources of information in preference to the 6-20 RPE scale (Fig 2). That does not mean perceived exertion is not an important factor in pacing decisions as predicted by many of the previous models. It does however, highlight to methodological complexities of investigating pacing decisions in terms of the acquisition and utilization of external referents, which can be easily observed using methods like eye-tracking, and the integration of internal bodily referents such as perceived exertion, which cannot be directly observed. This particular problem warrants innovative research using process-tracing methods of the kind described in much more detail elsewhere (37).

(Paragraph 38) This eye-tracking study has produced some important new data not entirely consistent with previous models of pacing about the attention to, and use of, feedback information. Nevertheless, there are a number of limitations associated with the laboratory-based nature of this experiment and the eye-tracking technology that was used. Cyclists in our study performed simulated time-trials on a static cycle ergometer under conditions where certain demands on the visual system were absent, for example those associated with balancing, navigating, negotiating hazards and avoiding collisions as reported elsewhere (51, 53). Furthermore, differences between laboratory and real-world visual behavior have been reported in several studies, the most notable findings being more centralized fixations in the real world (17), a tendancy to fixate on closer objects in the laboratory (17), and earlier longer object fixations in the realworld (10). Therefore, it cannot be assumed that, during road-based time-trials, the capacity to attend to performance information will be the same as reported in this experiment since it will compete with, or be interrupted by, other demands placed on the visual system. In the future, with careful configuration of mobile eye-tracking technology, it may be possible to measure the attention to performance information in field-based studies with associated improvements in ecological validity.

(Paragraph 39) Another limitation of this study relates to the link between visual information, decision-making processes and pacing behavior. While there is some evidence that what individuals look at is associated with their choices (16,26,43,44), it is unclear whether visual attention influences choice or simply reflects a choice that has been made (44). In our study the issue is further complicated by the difficulties of quantifying a pacing choice, since the method of detecting a meaningful change in pace from either speed or power time-series data is mathematically complex (41). Even if it were possible to precisely identify moments where a decision had been made to increase or decrease pace, decisions to maintain pace would clearly be impossible to detect, as they would not be indirectly reflected in time-series data. In this study, conclusions about the link between visual attention and pacing decisions, are deduced from the associated changes in vision and pace observed at a segment-by-segment level. In future, greater precision about the association between visual attention to performance information and pace could be investigated by setting up experiments were cyclists are presented with pacing dilemma where their decision to act can be pinpointed in time.

(Paragraph 40) Finally, with regards to information acquisition and decision-making during endurance sport, further consideration is needed regarding fatigue related constraints on visual behavior as predicted in Newell's model (39) because they are often overlooked (56). A relationship between fatigue and declining visual attention was found in one interesting study where increased levels of exertion among biathletes was associated with reduced visual behavior before making a rifle shot (54). Saccadic eye-movements are so fast and energetically efficient (47) that they are less likely to be responsible for such effects compared to high-order cognitive processes such as attention allocation mechanisms which have themselves been found to become fatigued as characterized by reduced capability to suppress irrelevant external cues (13). Such factors are likely to impact information acquisition and decision-making during endurance sport and warrant further investigation.

Conclusions

(Paragraph 41) Although perhaps counterintuitive, this study challenges the degree of importance placed on knowledge of the endpoint to pacing in previous models. This is especially true for experienced cyclists for whom distance feedback was looked at secondary to, but in conjunction with information about speed. Novice cyclists appear to have a greater dependence upon distance feedback, which they look at for shorter and more frequent periods of time than the experienced cyclists. Experienced cyclists are more selective in the information they refer to during a time-trial and they are also more consistent in the combination of primary and secondary information they use, and more consistent between various phases of a time-trial. The difference in information acquisition behavior observed in this study may reflect differences in motivational regulators, with experienced cyclists perhaps focusing more strongly on performing at the fastest speed and novices focusing on completion of the distance.

(Paragraph 42) This study is the first to directly measure cyclists' information acquisition behavior during a time-trial and the data shows that the information athletes attend to and use during self-paced endurance tasks is much more complex than previously assumed and not necessarily dominated by knowledge of the endpoint. The limitations associated with this study are that it cannot be assumed information acquisition would be the same during a road-based time-trial. There are also improvements to the analysis of time-series performance data that are needed to reveal hidden moments where a decision to alter pace has been made so that corresponding gaze behavior can be interrogated with greater precision. Nevertheless, this study has produced some exciting new insights about the information acquisition strategies of experienced and novice cyclists, as well as a new method for investigating visual attention and decision-making during paced exercise.

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Figure Legends

Figure 1. Overall time-trial performance (A) and time-trial pacing by segment for familiarization (B) and time-trial 1 (C).

Figure 2. Novice and Experienced total gaze duration data (A) and average gaze frequency (B) for primary (most looked at) through to nonary (least looked at) information sources calculated over the full 16.1 km distance for time-trial 1 (A) The type of information looked at with the corresponding number of subjects is presented alongside the data points in 2A for primary to tertiary sources but not included for quaternary to nonary sources. * denotes $P<0.05$; ** denotes $P<0.01$; *** denotes $P<0.001$.

Figure 3. Experienced versus novice segment-by-segment time-trial 1 total gaze duration data for primary (A), secondary (B) and tertiary information sources (C). * Denotes $P<0.05$; ** denotes $P<0.01$; *** denotes $P<0.001$; NS denotes not significant.

Figure 4. Experienced versus novice segment-by-segment time-trial 1 average gaze frequency for primary (A), secondary (B) and tertiary information sources (C). * Denotes $P<0.05$; ** denotes $P<0.01$; *** denotes $P<0.001$; NS denotes not significant.

Table 1

Table 1. Mean performance, heart rate and RPE time-trial data for group, trial and segment

		0-4 km		4-8 km		8-12 km		12-16.1 km		Overall	
		Novice	**Experience**	**Novice**	**Experience**	**Novice**	**Experience**	**Novice**	**Experience**	**Novice**	**Experience**
Speed (km/hr)	TT_{FAM}	31.2(2.7)	34.9(1.8)	31.3(3.2)	34.4(1.8)	31.3(3.3)	34.2(1.5)	32.2(2.3)	34.5(1.5)	31.5(2.8)	34.5(1.5)
		NS	NS	*	NS	**	NS	*	NS	**	NS
	TT_{EXP}	31.8(2.6)	34.9(1.8)	32.0(2.8)	34.8(1.9)	32.0(2.4)	34.6(2)	32.6(3.1)	35.2(1.9)	32.1(2.7)	34.9(1.8)
		**		*		**		*		**	
		**		**		*		**		**	
Completion Time (s)	TT_{FAM}	465(45)	413(21)	464(57)	418(22)	465(59)	421(19)	459(38)	426(18)	1854(193)	1680(75)
		NS	NS	*	NS	**	NS	*	NS	**	NS
	TT_{EXP}	455(42)	413(21)	452(45)	414(23)	452(37)	416(25)	455(52)	419(23)	1816(176)	1663(90)
		**		*		**		*			
		**		**		**		**		**	
Power (W)	TT_{FAM}	201(42)	261(39)	200(46)	256(38)	200(48)	257(27)	214(38)	267(23)	204(42)	260(30)
		NS	NS	*	*	**	NS	*	NS	**	*
	TT_{EXP}	210(41)	272(29)	212(44)	265(34)	210(38)	263(28)	223(46)	272(32)	214(42)	268(29)
		**		**		**		*		**	
		**		**		**		*		*	
Cadence (rpm)	TT_{FAM}	85(10)	97(5)	86(11)	98(4)	86(12)	104(17)	89(10)	96(2)	86(11)	99(3)
		NS	NS	NS	NS	NS	NS	NS	NS		
	TT_{EXP}	77(17)	95(8)	85(11)	95(7)	86(11)	96(6)	88(11)	96(7)	84(9)	96(7)
		**		*		*		*		**	
Heart Rate (bpm)	TT_{FAM}	146(19)	148(19)	160(17)	163(15)	166(17)	166(14)	176(13)	171(12)	162(16)	162(15)
	TT_{EXP}	139(12)	145(12)	161(11)	162(14)	169(7)	162(26)	175(6)	172(17)	161(7)	160(16)
RPE	TT_{FAM}	12.9(0.7)	13.5(1.1)	14.6(0.6)	15.1(1.1)	16.2(0.9)	16.3(1.2)	18.7(0.8)	18.6(0.9)	15.6(0.6)	15.8(1.0)
	TT_{EXP}	13.0(0.9)	13.3(1.1)	15.0(1.3)	14.8(1.3)	16.2(1.3)	17.1(1.4)	18.9(0.9)	18.9(0.8)	15.7(1.0)	16.0(1.0)

Note: Post hoc-tests are only indicated where significant ANOVA interactions or main effects were found. NS - Not significant; *P<0.05; **P<0.01; ***P<0.001.

Table 2

Table 2. Individual gaze combinations of primary and secondary information sources.

ID	Primary-Secondary Combination for the Whole Time-Trial	*Group Code	Primary-Secondary Combination Change by Segment (4-8-12-16 km)	**Primary Dominance by Segment (%)	Different Primary Sources Used per Segment (N)	Primary Source Switches Between Segments (N)
Novices						
S13	DS	1	SD-DS-DS-PD	52-59-55-62	3	2
S3	DS		DT-DP-DS-DS	50-56-57-54	1	0
S8	DS		OV-DS-TS-DT	58-53-51-65	3	3
S10	DO	2	CD-HD-OD-DO	50-51-51-51	4	3
S11	DO		DO-DP-DO-DO	51-65-64-61	1	0
S12	DP	3	DP-DP-PD-DT	58-53-56-78	2	2
S7	PD	4	DV-PT-PS-DS	55-60-60-60	2	2
S9	SD	5	SD-SD-SO-SD	56-52-55-52	1	0
S6	VD	6	DP-VO-VO-DO	55-57-66-56	2	2
S1	TP	7	OT-PV-TP-DV	51-56-51-62	4	3
Mean				**54-56-57-60**	**2.3**	**1.7**
S.D.				3-4-5-8	**1.2**	**1.3**
Mode	**DS**		**##-##-##-DO**		**1**	**2**
Experts						
S24	SD	5	SD-SD-SD-SD	61-62-64-64	1	0
S25	SD		SP-SD-OD-SH	50-50-52-52	2	2
S26	SD		DS-DS-SD-SD	54-52-62-71	2	1
S30	SD		SO-SO-SD-SO	66-62-58-61	1	0
S32	SD		SD-SO-SO-SD	64-64-70-66	1	0
S22	SO	8	SD-ST-OS-SO	78-79-59-53	2	2
S27	SO		SD-SO-SO-SD	69-57-70-59	1	0
S21	SP	9	SP-SO-SP-DS	65-65-72-51	2	1
S28	SP		SP-SP-SO-SP	68-61-68-69	1	0
S23	PS	10	PS-PS-PD-SH	63-65-59-52	2	1
Mean				**64-62-63-60**	**1.5**	**0.7**
S.D.				8-8-7-8	**0.5**	**0.8**
Mode	**SD**		**##-SO-SO-SD**		**1**	**0**

Note - *Group code represents a specific combination of primary-secondary point of regard; **Dominance of the primary point of regard is expressed as a percentage of the combined gaze time for both primary and secondary points of regard. Primary-secondary point of regard combinations are represented by two letters, with each single letter being coded as follows: S=Speed; D-Elapsed DIstance; P=Power; C=Cadence; H=Heart Rate; T=Elapsed Time; R=Ratings of Perceived Exertion; V=Projector Simulation View and O=Other. ## Indicating mode shared by more than one category

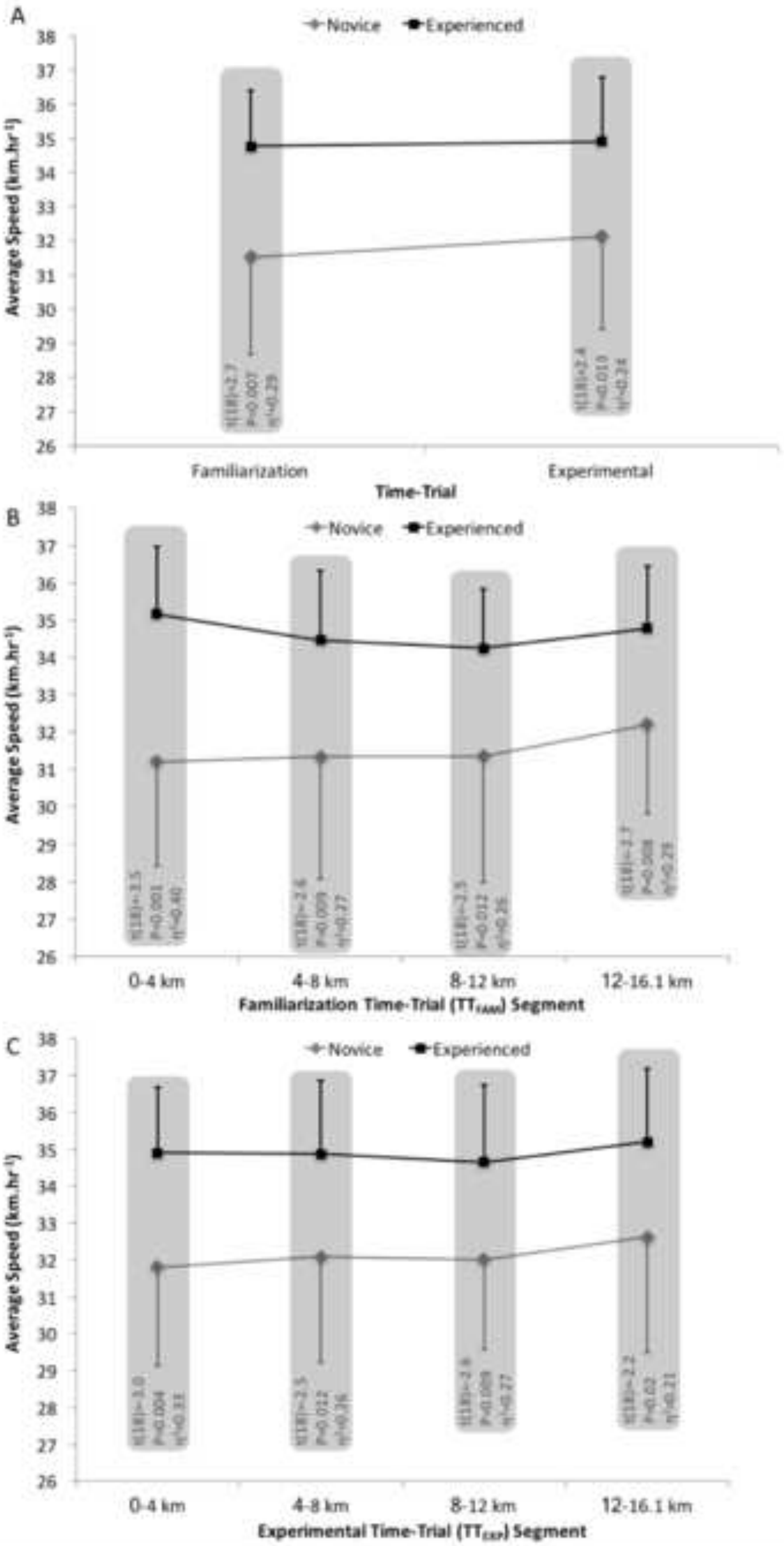

Figure 1. Overall time-trial performance (A) and time-trial pacing by segment for familiarization (B) and time-trial 1 (C).

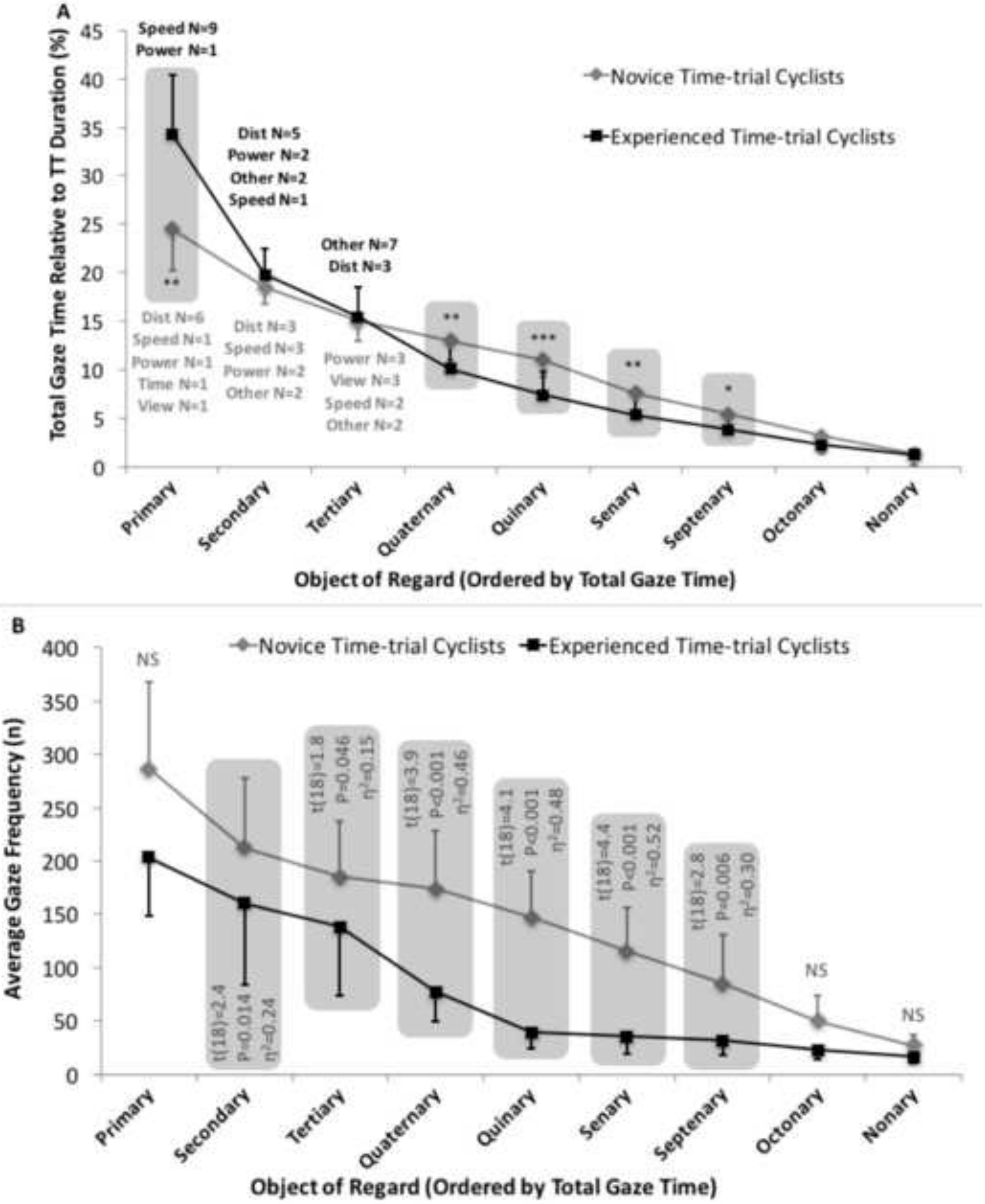

Figure 2. Novice and Expert total gaze duration data (A) and average gaze frequency (B) for primary (most looked at) through to nonary (least looked at) information sources calculated over the full 16.1 km distance for time-trial 1 (A) The type of information looked at with the corresponding number of subjects is presented alongside the data points in 2A for primary to tertiary sources but not included for quaternary to nonary sources. * denotes $P<0.05$; ** denotes $P<0.01$; *** denotes $P<0.001$.

Figure 3

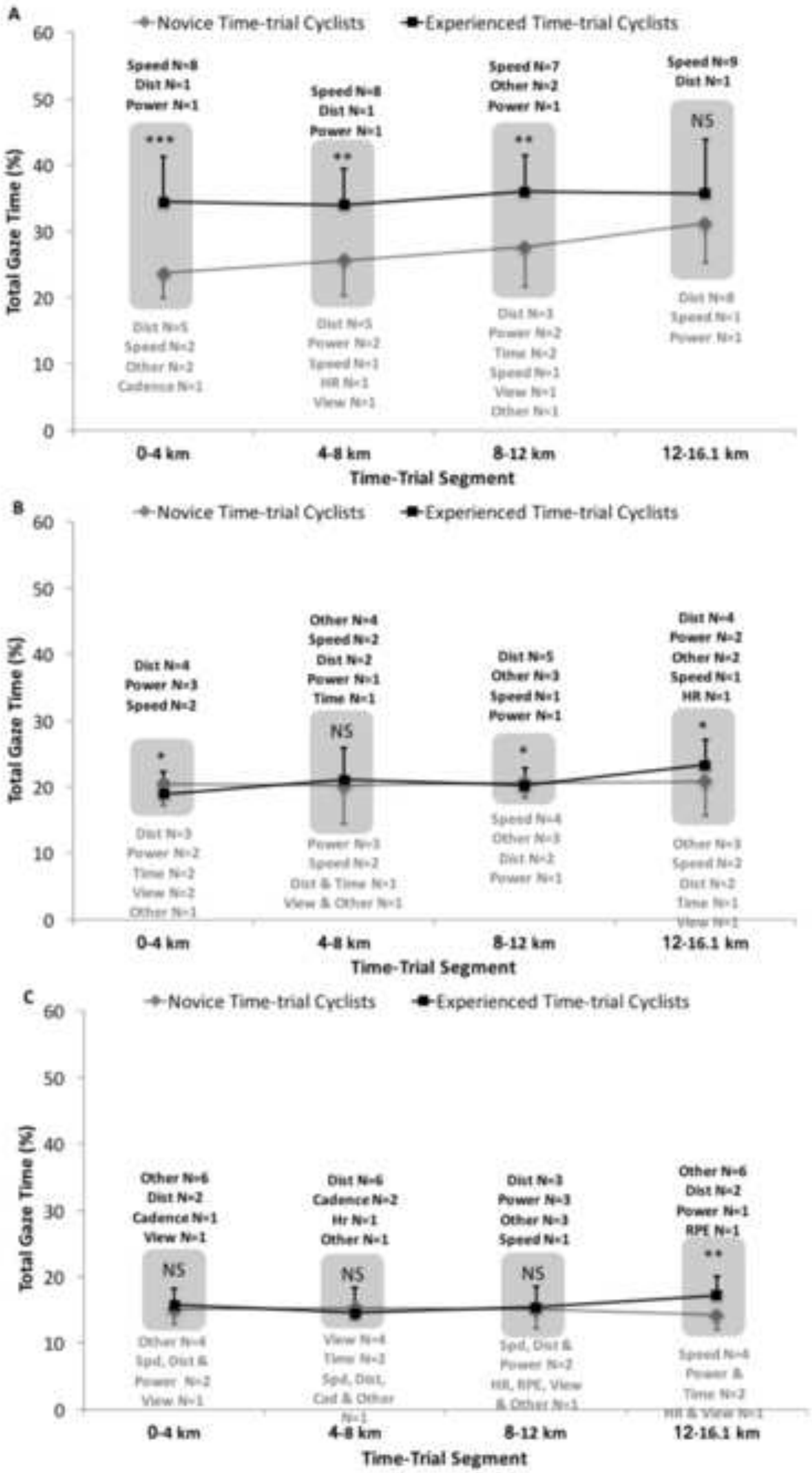

Figure 3. Expert versus novice segment-by-segment time-trial 1 total gaze duration data for primary (A), secondary (B) and tertiary information sources (C). * Denotes P<0.05; ** denotes P<0.01; *** denotes P<0.001; NS denotes not significant.

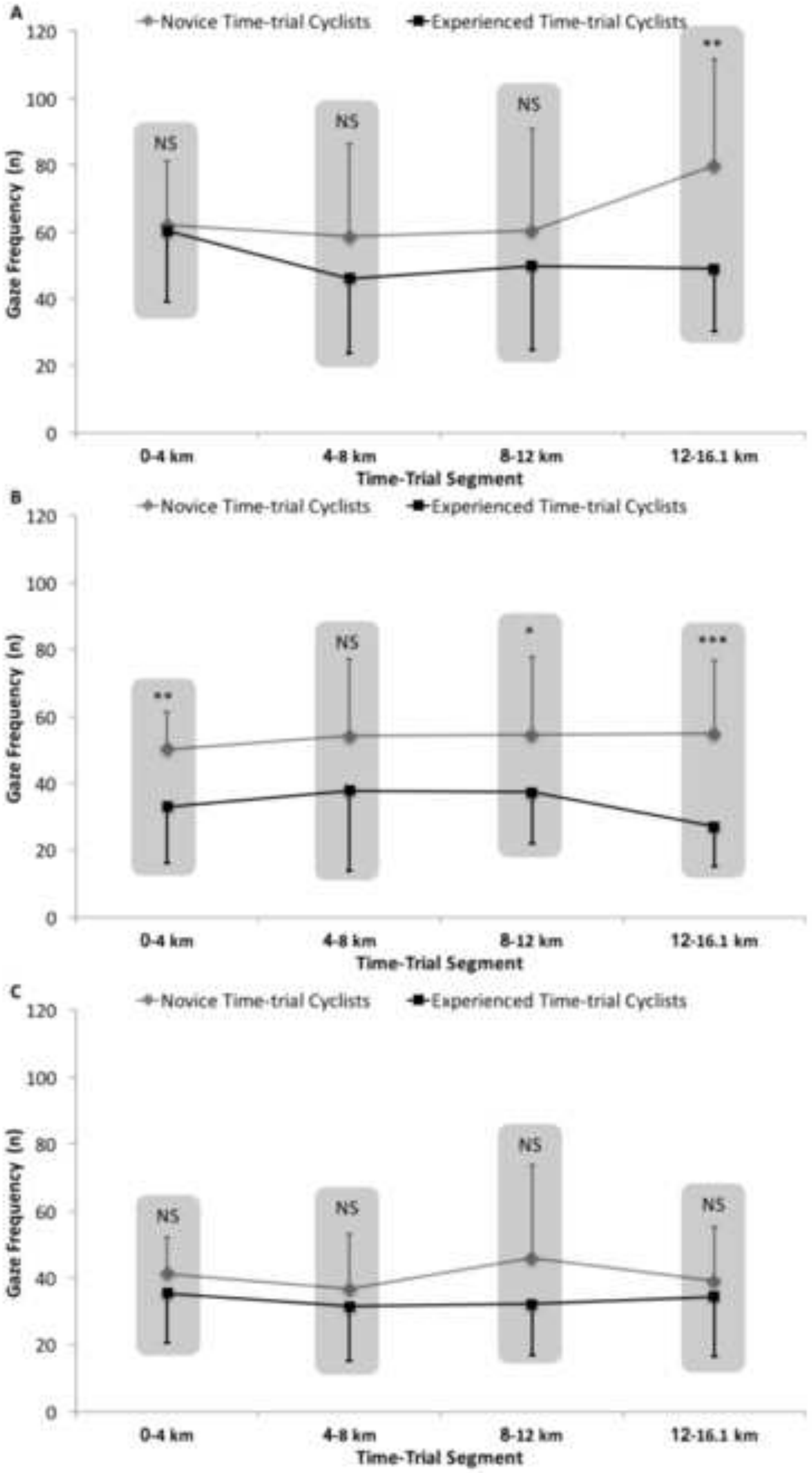

Figure 4. Expert versus novice segment-by-segment time-trial 1 average gaze frequency for primary (A), secondary (B) and tertiary information sources (C). * Denotes P<0.05; ** denotes P<0.01; *** denotes P<0.001; NS denotes not significant.