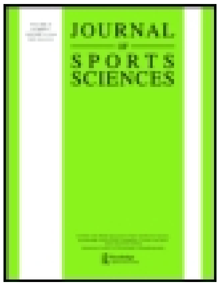

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Energy management using virtual reality improves 2000-m rowing performance

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Abstract

Elite-standard rowers tend to use a fast-start strategy followed by an inverted parabolic-shaped speed profile in 2000-m races. This strategy is probably the best to manage energy resources during the race and maximise performance. This study investigated the use of virtual reality (VR) with novice rowers as a means to learn about energy management. Participants from an avatar group (n = 7) were instructed to track a virtual boat on a screen, whose speed was set individually to follow the appropriate to-be-learned speed profile. A control group (n = 8) followed an indoor training programme. In spite of similar physiological characteristics in the groups, the avatar group learned and maintained the required profile, resulting in an improved performance (i.e. a decrease in race duration), whereas the control group did not. These results suggest that VR is a means to learn an energy-related skill and improve performance.

Keywords: *novice rowers, virtual environment, learning, fast-start strategy, race duration*

1. Introduction

Rowing is an endurance activity where performance, e.g. race duration over a particular distance, is determined by several factors. The overall fitness of athletes is the key. Rowing involves all major muscle groups (i.e. quadriceps, biceps, triceps and abdominal muscles) and requires cardiovascular endurance (Steinacker, 1993). However, body mass, technique, team coordination and the management of energy resources – the topic of this article – also influence the performance (Baudouin & Hawkins, 2002; Wing & Woodburn, 1995). Training programmes should be designed and implemented accordingly. Indoor rowing machines, i.e. ergometers, are popular alternatives to simulate the rowing action. They provide a means of training when on-water training is impossible. They are also precise and controllable systems that can assess athletes' fitness. While ergometers do not replicate the real action of rowing (lateral balance variation, water resistance or exact rowing movements such as sweep of the oar handles), they present a comparable training stimulus to on-water condition (de Campos Mello, de Moraes Bertuzzi, Grangeiro, & Franchini, 2009).

1.1. The fast-start strategy in elite-standard rowing

The race distance in conventional world championship is 2000 m, which lasts from 320 s for the best men rowers to 500 s or more for others. Elite-standard rowers tend to use a particular pacing strategy to cover the 2000 m in the shortest possible time. Garland (2005) recorded the performance of 1612 athletes during the 2000 Olympic Games and the 2001–2002 World Championships. Boat speed followed a fast-start profile, with the first 500 m performed at 103.0% of mean whole race speed and subsequent 500-m sectors were rowed at 99.0%, 98.3% and 99.7% of the mean speed, respectively (Figure 1).

For tactical and psychological reasons, this pacing strategy has several advantages. A fast-start strategy allows athletes to head a race, which is crucial, especially, for elite-standard rowers. Brown, Delau and Desgorces (2010) showed that 78% of winners in 2000-m race were first at the mid-point, and all were in the first three at that instant. Rowers can see other boats, avoid their waves and react to "attacks" from other competitors. There is a physiological rationale for the use of fast-start pacing

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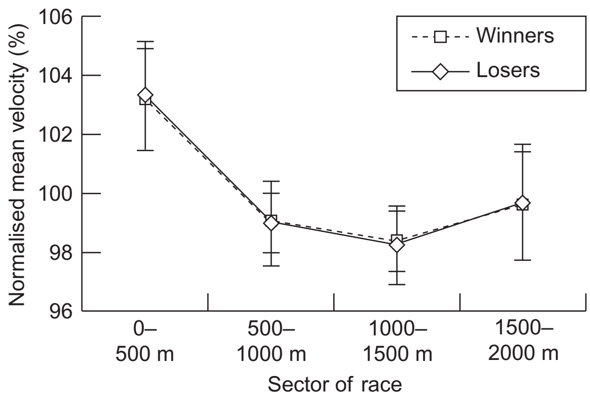

Figure 1. Ergometer race pace profiles comparing winners with losers for 2000 m. (Reprinted from "British Journal of Sports Medicine, Volume 39 (2005) 39–42, Garland, SW, Original Copyright © 2005, BMJ Publishing Group Ltd.", with kind permission from BMJ Publishing Group Ltd.)

strategies (Bishop, Bonetti, & Dawson, 2002; van Ingen Schenau, de Koning, & de Groot, 1992). Rossiter et al. (2002) demonstrated that at the onset of intense exercise, the oxygen uptake response ($\dot{V}_{O_2}$) increases proportionally to the decrease in phosphocreatine and ATP/ADP ratio. This results in an increased rate of glycolysis (Chasiotis, Bergström, & Hultman, 1987). Furthermore, it has been suggested that greater rates of phosphocreatine breakdown are required during the fast-start strategy in order to fuel the resulting higher speeds. This stimulates the resynthesis of ATP by oxidative processes and provides a stimulus for the increase in $\dot{V}_{O_2}$ (Bishop et al., 2002). Assuming that there is no change in the anaerobic production of ATP, faster $\dot{V}_{O_2}$ kinetics could improve performance by increasing the total ATP available to support the exercise.

1.2. VR accelerates the acquisition of skill

While physiological characteristics contribute to the selection of pacing strategy, pacing has to be learned. Brown et al. (2010) reported differences in outcome between strategies of elite- and lower-standard competitors. This suggests that the optimal profile described by Garland (2005) is a skill learned over time with training (i.e. repetitions) and appropriate feedback. In this study, we investigate the particular pacing strategy used by expert rowers and see if virtual reality (VR) technology can improve novice rowers' abilities to manage their energy stocks and thus improve rowing performance. The fast-start strategy seems to be a fundamental aspect for winning in 2000-m outdoor rowing races, and hence, it is important that novice rowers learn how to implement this strategy.

VR is a useful method for skill acquisition (Bergamasco, Bardy, & Gopher, 2012). Its effectiveness (in acquiring a new skill and improving an existing skill) has been demonstrated in diverse areas such as surgery (Howell, Conatser, Williams, Burns, & Eland, 2008), rehabilitation (Holden, 2005) and sport (Bideau et al., 2010; Ruffaldi et al., 2011). In VR, the environment is systematically under control and can be used to manipulate factors that affect athletes' performance, assess their influence, provide appropriate on-line feedback and ensure reproducible conditions. In this study, we used VR to train the fast-start strategy (see Garland, 2005) in a group of novice rowers and evaluated the consequences for rowing performance and retention. We expected (i) a better management of energy consumption in the group benefiting from VR for the same quantity of training (i.e. distance performed) and (ii) a positive transfer of that management skill to a new distance (i.e. 2500-m race).

2. Methods

2.1. Participants

Fifteen novice participants (men) (Table I) with no rowing experience completed the protocol and constituted the convenience sample. This selection guaranteed that participants were physiologically equivalent (i.e. ensured by the $\dot{V}_{O_2}$ max test) and did not adopt a priori the to-be-learned fast-start profile. They had no health problems and were affiliated to a sports federation (excluding the rowing federation). Ethics' approval was provided by the regional ethic review board (*Comité Consultatif de Protection des Personnes de Nîmes Sud-Méditerranée 3*). Participants were remunerated 50 € for their involvement.

2.2. Displays and experimental design

All testing and training was performed on an indoor rowing ergometer (*Concept2*, USA) at the EuroMov centre in Montpellier. As participants were novices, the outdoor rowing technique would have been too complex (i.e. maintenance of balance on water,

Table I. Participants' characteristics (Mean ± SD)

Variables/groups	Age (yrs)	Height (cm)	Body mass (kg)	$\dot{V}_{O_2}$ max ($mL \cdot kg^{-1} \cdot min^{-1}$)	StepMax (W)
Control	25.0 ± 2.8	177.9 ± 6.1	72.4 ± 5.9	56.4 ± 8.5	300 ± 50
Avatar	23.1 ± 2.2	177.3 ± 6.3	79.6 ± 14.9	46.9 ± 9.2	250 ± 50
Total	24.1 ± 2.6	177.6 ± 6.0	75.7 ± 11.2	52.0 ± 9.9	300 ± 50

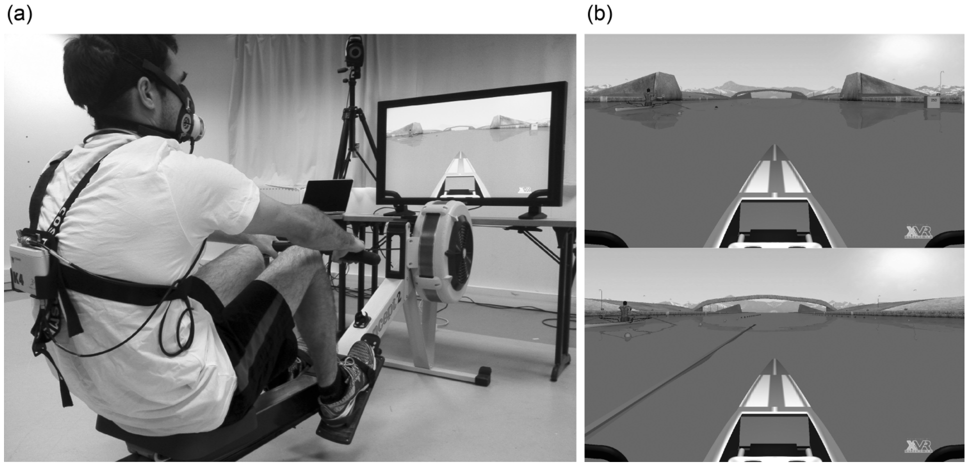

Figure 2. (a) Experimental design and (b) first-person's view for one participant of the avatar group. Participants had to maintain a constant distance between the avatar boat on the left part of the screen and their own boat. No line means that the speed is correct (upper panel); if a line appears, speed is inadequate (bottom panel). The colour of the line indicates to the participant to speed up or to slow down.

stroke effectiveness, etc.). A large screen (83 cm) was placed in front of the seated participants and a dynamic virtual environment that simulated the stern of the boat in outdoor rowing was displayed (Figure 2). A virtual opponent boat was displayed for the avatar group. The image on the screen was similar to what participants would experience in outdoor rowing. As a result, the visual angle varied between 37° and 107° depending on the position of the ergometer seat along its course. The size of the screen allowed for a projection similar to the real objects' size. The simulation was continuously updated by the action of the participant on the *Concept2* handle. The *Concept2* computer was interfaced with the PC to gather real time data about on-going performance. The ergometer provided power output and estimates of boat motion when propelled with that power. The obtained boat position was used to set the virtual boat position in the virtual environment and evaluate the participant's distance from the virtual opponent.

In a first session, participants completed an incremental exercise test under medical supervision to determine their $\dot{V}_{O_2}$ max and the power output at $\dot{V}_{O_2}$ max (StepMax). During this session, the intensity was increased in increments of 50 W, each 3 min long, until participants could not continue. In a second session, they all completed 2000 m as quickly as possible (pre-test). Then, participants completed eight 2000-m (training sessions) races with at least 48 h break between each of them for over a period of 60 days. For the training sessions, participants were divided into two groups: the *control group* ($n = 8$) who followed an indoor rowing training that consisted of 2000-m races, with the instruction to complete the required distance as fast as possible. Participants of this group were not informed about the optimal pacing strategy described earlier and consequently adopted a spontaneous behaviour. The *avatar group* ($n = 7$) benefitted from energy management information represented by an avatar boat visible on the screen (Figure 2(b)). Participants of the *avatar group* were instructed to track the virtual boat, whose speed was previously individually set to follow the appropriate to-be-learned speed profile along the 2000-m race, calculated from the mean speed recorded at pre-test. The maintenance of a constant interval of 24 m (±2 m) was considered as a correct interval for speed maintenance, and participants received on-line feedback in the form of a red or green line between the two boats when the interval was too short (participants were too slow) or too large (participants were too fast), respectively. The virtual boat was gradually removed by steps of 250 m during the training sessions: visible during the entire race at Session 1, it only became visible during the first 250 m at Session 8.

Then, all participants completed a 2000-m race in the shortest possible time. Performance before and after the training was compared to evaluate the effect of the speed profile accelerator. After 30 days, a retention test was performed to check if the learned speed profile was maintained. After another 30 days, participants completed a 2500-m race in the shortest possible time (transfer test) to assess the transferability of the learned speed dynamics to a race of longer duration. Given that our study covered 120 days in total, an outdoor protocol would have been sensitive to several climatic factors (temperature, wind, rain and cold) that would affect the results. Therefore, the training protocol was completed during indoor rowing in order to minimise variations attributable to groups, sessions and participants.

2.3. Data acquisition and variables

During $\dot{V}_{O_2}$ max-, pre-, post-, retention and transfer tests, oxygen uptake ($\dot{V}_{O_2}$), carbon dioxide production ($\dot{V}_{CO_2}$) and minute ventilation ($\dot{V}E$) were recorded and analysed continuously breath by breath by an automated system (K4b^2, Cosmed, Rome, Italy). The gas analysers were calibrated before and verified after each test according to manufacture specifications (K4b^2 instruction manual) using room air and known gas concentrations (16% O_2 and 5% CO_2). The air volume was calibrated with a 3-L syringe.

Split times at 500, 1000 and 1500 m and finishing times were used to determine speeds ($m \cdot s^{-1}$) during the pre-, post- and retention tests. For the transfer test, sectors were divided by a lag of 625 m (625, 1250, 1875 m and finish line). For all tests, we also calculated the mean speed of the whole race to determine from the expert profile (i.e. described by Garland, 2005) the anticipated speed of each sector. Then, the calculated and anticipated absolute speeds from the model were compared to determine if participants adopted the expert strategy.

Hence, the outcome measures for each participant in each session were race variables (race duration, mean power output, mean pace and StepMax), race strategy obtained from *Concept2* and the ventilatory and energy variables ($\dot{V}_{O_2}$ max, $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$, $\dot{V}E$, $\dot{V}E/\dot{V}_{O_2}$, $\dot{V}E/\dot{V}_{CO_2}$, energy consumption) obtained from the K4b^2 with an error of ±0.2%.

2.4. *Statistical analysis*

A Student's *t*-test compared $\dot{V}_{O_2}$ max values between groups, and a Mann–Whitney test compared non-parametric values (i.e. StepMax).

Race, ventilatory and energy variables were compared via a mixed-design factorial (Sessions × Groups) ANOVA with repeated measures. A *t*-test compared the performance in the transfer-test between the two groups. Speed profiles were compared via a mixed-design factorial (4 Sessions × 4 Sectors × 2 Groups × 2 Models) ANOVA with repeated measures. The level set for significance was $P < 0.05$. For a more detailed analysis of main and interaction effects, Scheffe's post hoc comparisons were performed when necessary. In addition, effect sizes were expressed using generalised eta square (η^2_G; Bakeman, 2005; Olejnik & Algina, 2003) to assess the practical utility of the results.

3. Results

3.1. $\dot{V}_{O_2}$ max *incremental test*

Statistical analyses showed no difference in $\dot{V}_{O_2}$ max ($t(13) = 1.92$, $P > 0.05$) and StepMax ($U = 24.50$, $P > 0.05$) between the avatar and the control groups (Table I). The two groups were thus equivalent in terms of their initial physiological characteristics.

3.2. *Race, ventilatory and energy variables*

3.2.1. Pre-, post- and retention tests. The analysis revealed an interaction between Sessions and Groups in race duration ($F_{(2,12)} = 4.15$, $P < 0.05$, $\eta^2_G = 0.409$) (Figure 3(a)). Notably, the avatar group produced better performances at the post- and retention tests than at the pre-test (respectively, $P < 0.001$ and $P < 0.01$), with no difference between post- and retention tests ($P > 0.05$). This indicates that the improvement of performance was maintained after a period of 30 days. In contrast, the control group completed the requested 2000-m races over the various sessions (at best $P = 0.22$) with little variations in times, suggesting that the amount of practice itself was not sufficient to increase the performance. The analysis showed no

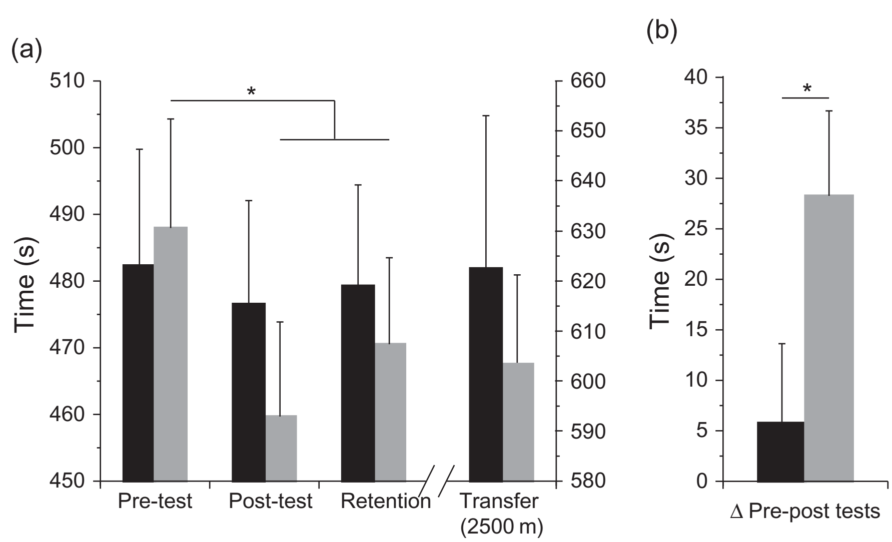

Figure 3. (a) Race duration for the control group (black) and the avatar group (grey) at pre-, post-, retention and transfer tests and (b) pre–post performance gain for the control group (black) and the avatar group (grey).

Note: $^*P < 0.05$.

Table II. Mean ± SD for the different race, ventilatory and energy variables.

Sessions/variables		Pre-test	Post-test	Retention test	Transfer test
$\dot{V}_{O_2}$ (L · min^{-1})					
	Control	3.48 ± 0.65	3.33 ± 0.51	3.18 ± 0.44	3.12 ± 0.62
	Avatar	3.18 ± 0.34	3.46 ± 0.67	3.31 ± 0.51	3.58 ± 0.56
$\dot{V}E$ (L · min^{-1})					
	Control	103.95 ± 21.56	106.16 ± 16.44	104.12 ± 16.66	91.04 ± 22.80
	Avatar	112.37 ± 21.99	129.21 ± 27.95	118.93 ± 26.41	117.95 ± 29.04
$\dot{V}E/\dot{V}_{O_2}$					
	Control	30.06 ± 3.16	31.86 ± 3.65	32.73 ± 1.60	28.75 ± 4.02
	Avatar	35.04 ± 4.92	37.69 ± 8.62	35.56 ± 4.46	32.60 ± 4.25
$\dot{V}E/\dot{V}_{CO_2}$					
	Control	29.24 ± 3.22	27.96 ± 1.59	30.16 ± 2.15	27.85 ± 2.54
	Avatar	31.03 ± 4.81	32.81 ± 4.45	31.12 ± 4.05	31.78 ± 6.20
Energy (kJ)					
	Control	823 ± 139	750 ± 118	732 ± 113	822 ± 184
	Avatar	771 ± 89	789 ± 153	737 ± 142	935 ± 219
Pace (strike · min^{-1})					
	Control	36.00 ± 2.56	35.50 ± 3.89	35.00 ± 2.62	34.75 ± 1.49
	Avatar	32.43 ± 2.44	35.14 ± 2.54	34.14 ± 2.34	34.00 ± 2.00
Power output (W)					
	Control	228 ± 39	233 ± 50	239 ± 41	232 ± 60
	Avatar	222 ± 54	266 ± 54	225 ± 51	244 ± 56

difference in performance between the groups at pre- ($P = 0.06$), post- ($P = 0.10$) and retention tests ($P > 0.05$). However, there was a tendency for the control group to row slightly faster at pre-test than the avatar group ($P = 0.06$), which might explain the lack of difference between the two groups at post-test. For this reason, a *t*-test compared the gain in performance between pre- and post-tests for the two groups and indeed revealed a higher gain for the avatar group ($t(13) = 2.79$, $P = 0.01$, $\eta^2_G = 0.357$) (Figure 3(b)).

There was no difference in pace and power output variables (at best $P = 0.15$) between the sessions, suggesting that the gain in performance observed for the avatar group was not due to a change in the force–frequency relationship. Moreover, ventilatory and energy variables remained unchanged over sessions (at best $P = 0.09$), indicating that the better gain in performance reported for the avatar group was not linked to an increase in oxygen or energy consumption (Table II).

3.2.2. Transfer test. Analyses revealed no difference between groups in race, ventilatory and energy variables (at best $P = 0.21$).

3.3. *Race strategy*

There was an interaction for speed profile among sessions, sectors, groups and models ($F_{(9,54)} = 2.94$, $P < 0.01$, $\eta^2_G = 0.329$). We detail the session-by-session effects in the following section.

3.3.1. Pre-test. As illustrated in Figure 4(a), both groups completed the first and last 500 m, respectively, slower and faster than the anticipated profile (control group: at worst $P < 0.001$; avatar group: at worst $P = 0.006$). This result suggests that the two groups adopted a speed profile with a slow start and a fast finish and hence did not adopt spontaneously the optimal profile described by Garland (2005). The similarity between groups and dissimilarity with the model at pre-test are important results that can be tested again after training in VR (at post- and retention tests).

3.3.2. Post- and retention tests. Control group: At post-test (Figure 4(b), left panel), participants started the 2000-m race slower ($P < 0.001$) and finished it faster ($P < 0.05$) than the model. They were also slower than the model during the first 500 m of the retention test ($P < 0.001$, Figure 4(c), left panel). Together, these results indicate that the control group did not progress towards the fast-start strategy during the training period and that they maintained a constant speed profile at the retentiontest.

Avatar group: Contrary to the pre-test observations, the analysis revealed no difference between the speed profile of the avatar group and the model at post-test (at best $P = 0.11$, Figure 4(b), right panel), indicating that participants from this group learned and adopted the expert speed profile. At the retention-test, participants from this group were faster than the model during the first 500 m ($P < 0.05$) but slower than the model during the third sector

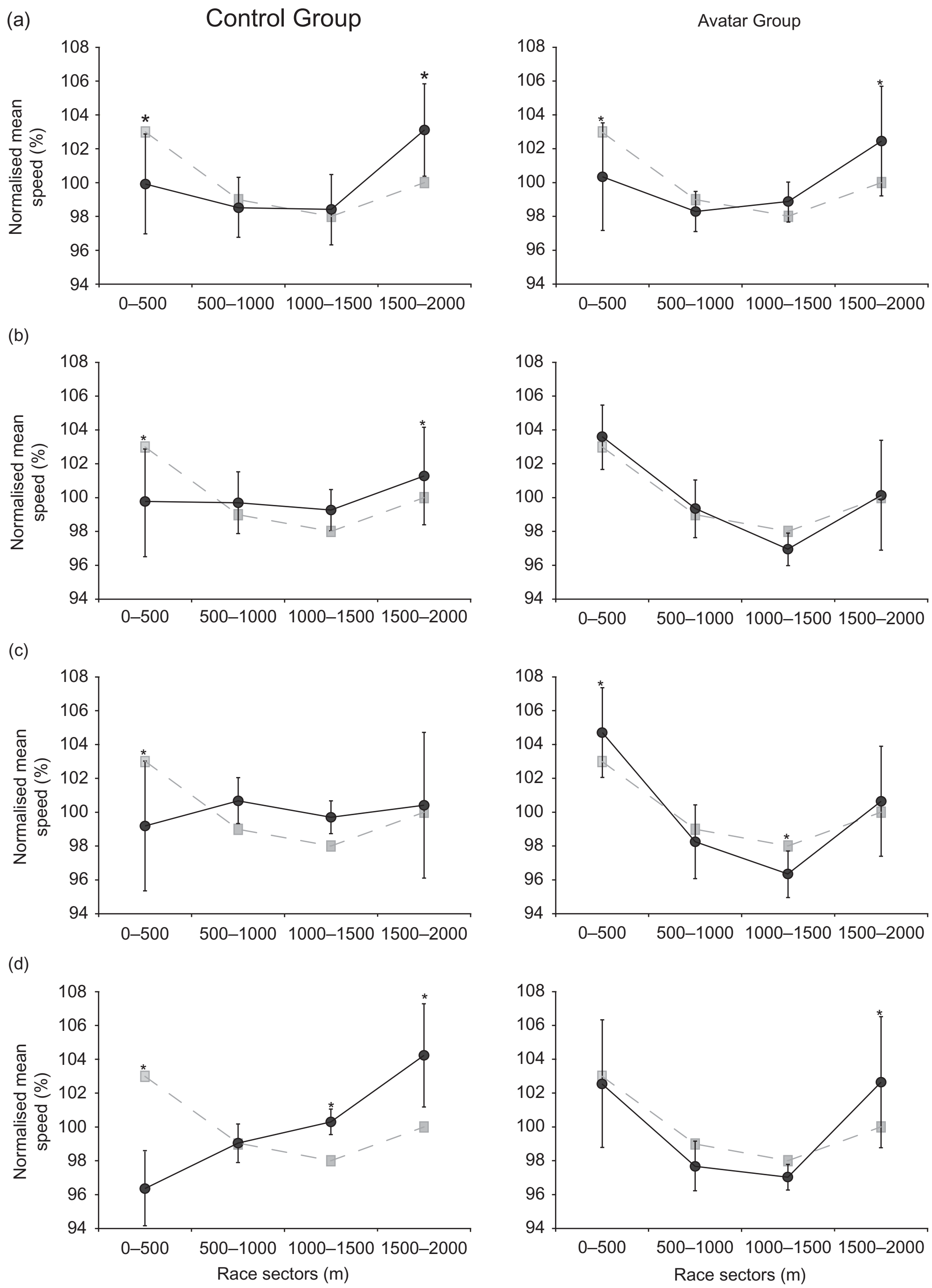

Figure 4. Speed profile over the four sectors of the 2000-m race in (a) pre-, (b) post-, (c) retention and (d) transfer tests comparing control group (black line, left four panels) or avatar group (black line, right four panels) with the expected profile (grey line).

Note: *Indicates significant differences ($P < 0.05$) between produced and expected profiles.

($P < 0.05$, Figure 4(c), right panel). Thus, participants of the avatar group learned and maintained the fast-start/fast-finish strategy, even 1 month later at the retention test, however, with some slight variation and compensation when compared with the performance at post-test.

3.3.3. Transfer test. The control group adopted a speed profile different from the model on the new distance. Indeed, they completed the first 625 m slower ($P < 0.001$) and the last two sectors faster than the model (respectively, $P < 0.05$ and $P < 0.001$, Figure 4(d), left panel). They also increased their boat speed gradually until the end of the race. This suggests that participants from the control group did not adopt the fast-start strategy but conserved some energy to increase their speed in a continuous manner and finish the race at top speed.

Conversely, the avatar group adopted a speed profile comparable to the model (Figure 4(d), right panel). They globally reproduced the learned fast-start strategy but conserved some energy to accelerate at the end of the race on the new distance. Indeed, they completed the last 625 m faster than the model ($P < 0.001$).

4. Discussion

In this study, we selected the distance of 2000 m because it is used in major rowing events (i.e. World Championship and Olympic Games) and corresponds to the distance for which the elite-standard strategy was documented (Garland, 2005). Neither of our two novice groups adopted spontaneously the fast-start strategy reported by Garland (2005), as illustrated in Figure 4(a). However, the two groups adopted distinct race strategies after the training period. Participants from the control group, who received no instruction, managed their effort using a secure even-paced strategy, maintaining the same speed along the race in post- and retention tests (Figure 4(b and c) left panels). This result can be explained by a lack of knowledge of the optimal pacing strategy or instruction. Although Garland (2005) and Brown et al. (2010) reported different pacing strategies for indoor and outdoor rowing races, both showed fast-start strategy as a possible consequence of different goals pursued by rowers (i.e. finish as fast as possible during indoor races and finish first during on-water races). The strategy described by Garland (2005) for on-water races has physiological and psychological advantages, as it takes the athletes to the front of the race. This second advantage does not occur during indoor rowing and can explain why our novice rowers adopted an even-paced profile rather than a fast-start profile, which, nevertheless, constitutes the optimal profile. Conversely, participants from the avatar group received continuous fast-start energy-related visual information. Our results showed that they quickly adopted the fast-start strategy and maintained their speed along the requested profile (Figure 4 (b and c), right panels), consistent with the results reported by Garland (2005) on experts. Because the initial physiological characteristics and the global energy consumption were identical for both groups at the pre-test, the differences in gain of performance observed after training can be attributed only to the learned pacing strategy. This result validates the suggestion by Foster, Schrager, Snyder, and Thompson (1994) and Fukuba and Whipp (1999) that pacing strategies have major effects on performance in most endurance sports and contribute to determining the winner in spite of little physiological difference between the elite-standard competitors. Moreover, our results showed that the fast-start strategy can be considered as a skill requiring learning time, repetition and feedback, and participants from the control group did not adopt it even after eight training sessions (c.f. post-test). We also demonstrated that this pacing strategy can be learned rapidly (i.e. in eight sessions), even perhaps in shorter time if we had moved the avatar boat by steps larger than 250 m.

All these points evidence that VR is useful to learn a specific race strategy during rowing and contributes to performance improvements. This conclusion supports recent studies that have demonstrated the effectiveness of VR in the acquisition of abilities or the reinforcement of existing abilities (Bergamasco et al., 2012) in sports (Bideau et al., 2010) as well as in other fields (Holden, 2005; Seymour et al., 2002; Watson, Butterfield, Curran, & Craig, 2010). Here, we extend the range of skills that VR can positively impact on complex multi-dimensional skills sharing physiological, biomechanical and perceptual resources. We also demonstrated the persistence of our VR training over time (30 days).

de Campos Mello et al. (2009) reported equivalent energetic demands of 2000-m rowing races outdoor (i.e. on-water) and indoor when values are normalised by race time. Because the *Concept2* ergometer simulates conditions of a faster boat (Ergometer world record in 2000 m for heavyweight men is 336.6 s) as opposed to a "real" single scull (world record in 2000 m for heavyweight men is 393.3 s), a 2500-m test on an ergometer would be more appropriate to simulate a 2000-m test on water (Jürimaë, Maëstu, Jürimaë, & Pihl, 2000; Maëstu, Jürimaë, & Jürimaë, 2000). This is the main reason to use 2500-m race for our transfer-test. Our results indicate different strategies for the two groups. Participants from the control group adopted a "safety" pacing strategy with a slow start followed by a progressive acceleration throughout the race. The end spurt suggests that they controlled their effort by adopting a sub-optimal strategy. According to Atkinson, Peacock, St. Clair Gibson, and Tucker (2007), athletes spontaneously choose a starting strategy based on their knowledge of the duration for which the remaining effort is required. Given that participants from the control group did not have any experience of rowing, it is not surprising that they accelerated progressively so as to have enough energy to finish the race. Conversely, participants from the avatar group followed the global dynamics of the pacing strategy learned on 2000-m race, with a fast-start strategy accompanied by the conservation of some energy to accelerate at the end of the race. Thus, our virtual rowing situation revealed a positive transfer of the energy management skill, 2 months after the learning period.

Our study demonstrated the effectiveness of VR for the acquisition, retention and transfer of energetic skills and associated improvement in performance. The lack of rowing techniques of our participants and the necessity to complete our longitudinal protocol in standardised conditions led us to complete our protocol on an indoor rowing ergometer. A useful development would be to test the transferability of the learned strategy in on-water situations.

The superiority of the fast-start strategy over other pacing strategies has to be nuanced, however. In rowing, it seems to be the optimal strategy for experts (Garland, 2005; Secher, Espersen, Binkhorst, Anderson, & Rube, 1982) as well as for novices (our data), but in other sports, a slow start may be beneficial (Mattern, Kenefick, Kertzer, & Quinn, 2001). For instance, Wilberg and Pratt (1988) reported distinct race profiles between winners and losers among cyclists performing a 1000-m time trial and suggested that losers accelerate too rapidly in the beginning of the race. Indeed, the importance for competitors to regulate their speed in order to cover the distance as fast as possible for all considered athletic events has been repeatedly pointed out (Abbiss & Laursen, 2008; Joseph et al., 2008; St. Clair Gibson, Schabort, & Noakes, 2001). Several pacing strategies have been reported for middle- to long-distance events from 20 to 60 min in duration (Abbiss & Laursen, 2008; Foster et al., 2004), showing that for long-duration events, an even-paced strategy is the optimal strategy (Abbiss & Laursen, 2008; de Koning, Bobbert, & Foster, 1999; Thompson, MacLaren, Lees, & Atkinson, 2004). Thus, the type of activity and the race duration are important factors that contribute to the appropriate choice of the pacing strategy. Notably, our VR energy management system can be adapted to various sports and race durations and can therefore potentially contribute to accelerate the learning of energy management in a wide range of training situations.

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