

# Elite Athletes Refine Their Internal Clocks

Yin-Hua Chen and Paola Cesari

Evaluating time properly is crucial for everyday activities from fundamental behaviors to refined coordinative movements such as in sport playing. Lately the concept of the existence of a unique internal clock for evaluating time in different scales has been challenged by recent neurophysiology studies. Here we provide evidence that individuals evaluate time durations below and above a second based on two different internal clocks for sub- and suprasecond time ranges: a faster clock for the subsecond range and a slower one for suprasecond time. Interestingly, the level of precision presented by these two clocks can be finely tuned through long-term sport training: Elite athletes, independently from their sport domains, generate better time estimates than nonathletes by showing higher accuracy and lower variability, particularly for subsecond time. We interpret this better time estimation in the short durations as being due to their extraordinary perceptual and motor ability in fast actions.

**Keywords:** time perception, time evaluation, time reproduction, elite athlete

It is well-known that elite athletes develop skills necessary to decode events in the space–time domain, such as catching a flying baseball (McBeath, Shaffer, & Kaiser, 1995), performing an attacking forehand drive in table tennis (Bootsma & Van Wieringen, 1990), or anticipating the behavior of others such as predicting the fate of a basketball shot (Aglioti, Cesari, Romani, & Urgesi, 2008). In other words, outstanding motor expertise is seamlessly linked to perception which draws on detection of spatial and temporal information. In general for movement evaluation, space and time are considered inseparable, so we set out to understand the nature of time evaluation when it is in isolation from spatial dimensions and when testing exceptional timekeepers such as sport players. We tackled this issue by investigating elite athletes' ability to reproduce different times of exposure of a static visual display.

For time estimation, two scalar properties have been proposed. The first one is mean accuracy, suggesting that the estimated time changes linearly, and usually accurately, as the sample time varies. The second property indicates that the preci-

---

Chen is with the Research Center for Mind, Brain and Learning, National Chengchi University, Taipei City, Taiwan, and the Dept. of Neurological and Movement Sciences, University of Verona, Verona, Italy. Cesari is with the Dept. of Neurological and Movement Sciences, University of Verona, Verona, Italy. Address author correspondence to Paola Cesari at [paola.cesari@univr.it](mailto:paola.cesari@univr.it).

sion of time estimation, usually in the form of a Weber-fraction-like measure such as the coefficient of variation (CV), remains constant as sample time varies (see Allan, 1998, and Wearden & Lejeune, 2008, for reviews). These two properties were considered as evidence of the existence of one centralized internal clock for all timescales (e.g., see Gibbon, Church, & Meck, 1984). However, more recently, the “one-clock” notion has been challenged by numerous reports in neuroscience which, by providing the evidence of distributed brain circuits for time processing, suggest the existence of multiple clocks for multiple timescales (for a review, see Mauk & Buonomano, 2004). For instance, cerebellum impairment distorts the perception for subsecond durations but not for longer ones (Ivry & Spencer, 2004; Koch et al., 2007), and pharmacological manipulation affects time perception differently in the sub- and suprasedond range of time (Matell, King, & Meck, 2004; Rammsayer, 1999). In general, subsecond durations are timed at a subcognitive level, particularly in the motor brain areas associated with the refined control of coordinative movements such as supplementary motor area (SMA), primary motor cortex, and cerebellum (Ivry & Spencer, 2004; Lewis & Miall, 2006), while durations above a second are timed by cognitive processes requiring working memory and attention and which are related to different cortical structures such as basal ganglia, prefrontal regions, and parietal regions (Buhusi & Meck, 2005; Ivry, 1996; Lewis & Miall, 2003, Vicario et al., 2010; Vicario, Martino, & Koch, 2013; Wiener et al., 2010). In line with this notion, we expected that the impact of sport training would refine athletes’ internal clocks in both the sub- and suprasedond range of time since long-term practice of physical exercise has been shown to induce adaptive functional and structural changes in the brain involving both motor- and memory-related networks (e.g., Chaddock et al., 2010; Jacini et al., 2009; Jäncke et al., 2009; Lambourne, 2006; Wei, Zhang, Jiang, & Luo, 2011).

A major limitation in the time perception literature is that for the most part only one temporal duration in each range of time (sub- and suprasedond time) has been considered when testing the existence of the two clocks’ mechanism. Here, to get a deeper insight into the workings of the two hypothetical clocks, we applied 16 different time durations from 300 to 1,800 ms in 100-ms steps.

In sum, the purpose of this study is twofold: first, to corroborate the existence of the two hypothetical internal clocks, working above and below a second, by using a wide range of time durations; and second, to explore whether the accuracy and precision of these two clocks can be increased due to the long-term practice of physical exercise such as that followed by elite athletes. Thus, we recruited high-level fencers and pole-vaulters as groups of athletes and compared their performance with nonathletes. The selection of these two sports was aimed at investigating whether time estimation is influenced by the different training experiences that are typically referred to as “open-skill” (for fencing) or as “closed-skill” (for pole-vaulting) (Schmidt & Wrisberg, 2008). Indeed, while fencing requires athletes to fight against an opponent and perform within a highly unpredictable environment (Szabo, 1977), by contrast pole-vaulting is an individual sport and athletes are trained to find their own action time in a relatively stable environment (Ganslen, 1961). A comparison of the two groups of the athletes would allow us to observe whether the ability to estimate time is affected by specific perceptual–motor expertise.

## Methods

### Participants

Fifteen elite fencers (5 male and 10 female with a mean age of  $27.5 \pm 8.0$  years), 12 elite pole-vaulters (9 male and 3 female with a mean age of  $26.8 \pm 4.0$  years), and 23 nonathletes (10 male and 13 female with a mean age of  $28.0 \pm 4.7$  years) took part in this experiment. The three groups of participants did not significantly differ either by age,  $F(2, 49) = 0.18$ ,  $p = .84$ , or gender distribution,  $\chi^2(2) = 4.89$ ,  $p = .09$ . Elite fencers and pole-vaulters were recruited based on the criteria of having more than 7 years of training experience (for fencers  $16.2 \pm 8.8$  and for pole-vaulters  $11.2 \pm 3.3$  years of training) and active participation in competition at least at the national level. Nonathletes had no experience in sports at a competitive level. All participants had normal or corrected-to-normal vision and were naive about the purpose of the experiment. All of them gave written informed consent to the study in accordance with the procedure approved by the ethics committee of the Department of Neurological and Movement Sciences, University of Verona, Italy.

### Task

Participants were instructed to look at a visual stimulus that flashed for a specific temporal duration and to reproduce the duration using their index finger of the dominant hand by pressing and releasing the space bar of a computer keyboard (cf. Brown, 1995). No feedback was given.

### Materials and Procedure

The experiment was conducted in a small cubicle, insulated from external light and noise. Participants were seated opposite a 19-in. computer monitor ( $1,280 \times 1,024$ , 75 Hz) with a keyboard placed at a distance of 60 cm in front of them. The experimental program was written using MATLAB 7.1 and Cogent 2000, which assured millisecond accuracy for stimulus and reproduced time. The stimulus was an image of scrambled pixels ( $20 \times 16$  cm). It was displayed on a black background and located in the center of the screen for 16 different temporal durations from 300 to 1,800 ms in 100-ms steps, divided into the subsecond range from 300 to 1,000 ms and suprasedond range from 1,100 to 1,800 ms. A fixation cross was displayed for 2 s before the exposure of the stimulus. The task was explained to the participants by on-screen instructions, which were clarified when necessary by the experimenter. A few practice trials were given to ensure that the task was fully understood. The 16 different sample temporal durations were tested in a randomized order, and each of them was tested for eight repetitions for a total of 128 trials. The experimental procedure took approximately 1 hr.

### Data Analysis

Reproduced times were entered to fit two linear (bilinear) regressions as a function of test time durations in the subsecond range (8 levels, from 300 to 1,000 ms in 100-ms steps) and in the suprasedond range (8 levels, from 1,100–1,800 ms in 100-ms steps),

respectively, and to fit one single linear regression across all the sample times (16 levels, from 300 to 1,800 ms in 100-ms steps) to model the relationship between the reproduced times and sample times. To compare the goodness of fit between the bilinear and the single linear approach, the sums of squared residuals (SSRs) from the data points to the regressions of sub- and suprasedond ranges were calculated individually and added together and then compared with the SSR for the single linear regression (cf. Kagerer et al., 2002). A two-way repeated measures analysis of variance (ANOVA) was used; the within-subjects factor was the two SSRs of bilinear and single linear regressions, and the between-subjects factor was the three groups of fencers, pole-vaulters, and nonathletes. Slope values of the bilinear regressions were compared in a two-way repeated-measures ANOVA, with range of time (sub- and suprasedond) as the within-subjects factor and group (fencers, pole-vaulters, and nonathletes) as the between-subjects factor.

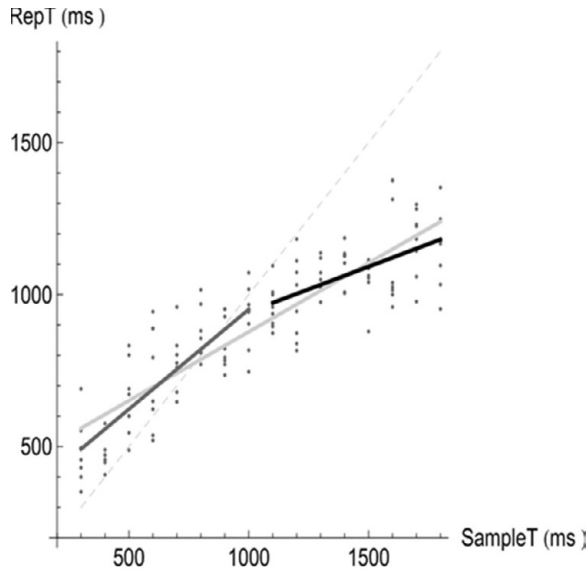
In addition we calculated the following: (1) the ratio between the absolute errors of the reproduced time and the respective sample time (AE ratio) to study participants' reproduction error and (2) the CV of the reproduced time as the percentage of standard deviation to the mean of the reproduced time to study participants' reproduction variability. For each variable, we calculated the mean for sub- and suprasedond ranges of time, respectively, and compared them in a two-way repeated-measures ANOVA with range of time (sub- and suprasedond) as the within-subjects factor and group (fencers, pole-vaulters, and nonathletes) as the between-subjects factor. SPSS 16.0 was used for statistical analyses. The significance level for all tests was set at  $p < .05$ . A Bonferroni adjustment was used when making multiple comparisons.

## Results

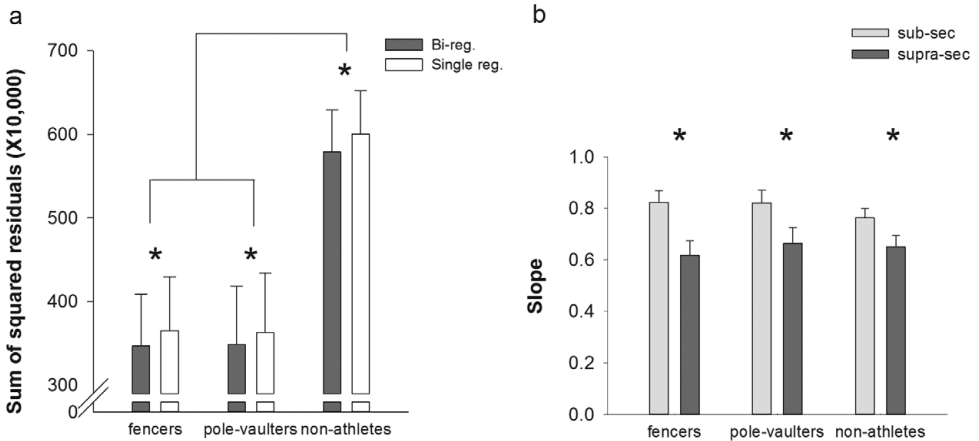
Before data fitting, for each participant, reproduced times were first trimmed to discard outliers outside the range of the mean plus or minus twice the standard deviation. This procedure resulted in the loss of 1.72% of all the data.

### Goodness of Fit of Biregressions and Single Linear Regression

Figure 1 illustrates an example of the reproduced times plotted as a function of 8 sample times in the subsecond range (regression line shown by a red solid line) and in the suprasedond range (shown by a green line) and a function of the total 16 sample times (shown by a black line). The two-way (2 approaches of fitting  $\times$  3 groups) repeated-measures ANOVA detected a significant main effect of fitting approach, showing that a bilinear approach resulted in a significantly lower SSR than the single linear one (4,247,234 vs. 4,426,359),  $F(1, 47) = 28.765$ ,  $p < .001$ . The main effect of group was also found significant,  $F(2, 47) = 5.698$ ,  $p < .01$ , with smaller SSR for both fencers and pole-vaulters than nonathletes (mean value of 3,559,856, 3,555,497, and 5,895,037 for fencers, pole-vaulters, and nonathletes, respectively). Comparisons between athletes (fencers and pole-vaulters) and nonathletes were significant,  $p$  values  $< .05$ , but the comparison between fencers and pole-vaulters was not,  $p = 1.00$ . The interaction effect was not found to be significant,  $F(2, 47) = 0.430$ ,  $p = .653$  (see Figure 2a).



**Figure 1** — One example of reproduced times of a pole-vaulter: data plotted as a function of 8 sample times in the subsecond range (regression line shown by gray solid line) and in the suprasedond range (black solid line) and as a function of the total 16 sample times (light gray solid line). The dashed light gray line denotes the identical line where the participant’s reproduced time equals the sample time.



**Figure 2** — (a) Average sum of squared residuals (SSR) for bilinear and single linear regressions of fencers, pole-vaulters, and nonathletes. Bilinear fitting shows the combined SSR from the regressions of the subsecond and suprasedond ranges of time. Note that the lower the value of SSR, the better the data fitting. Error bars indicate standard errors,  $*p < .05$ . (b) Average slope value of two regression lines fitted from data of the sub- and suprasedond ranges of time for fencers, pole-vaulters, and nonathletes. Error bars indicate standard errors,  $*p < .05$ .

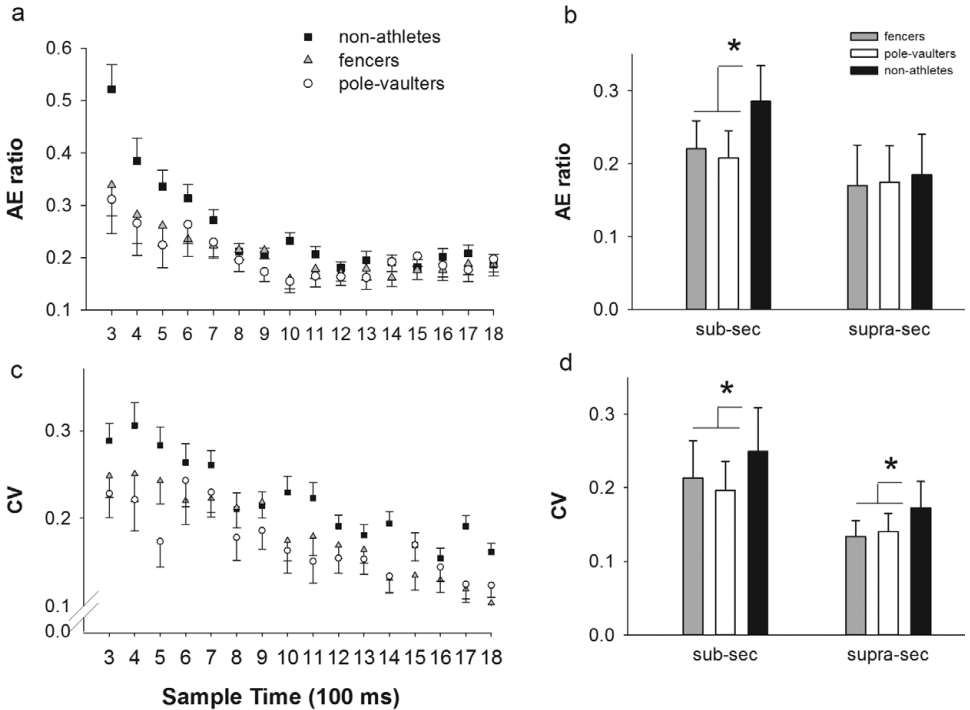
## Slope Difference Between the Biregressions

As shown in Figure 2b, the slope of subsecond regression was steeper than the slope of suprasedond regression. Indeed, the two-way (2 ranges of time  $\times$  3 groups) repeated-measures ANOVA detected a significant main effect of range, with significantly greater value for the subsecond range than for the suprasedond range (0.802 vs. 0.644),  $F(1, 47) = 17.818, p < .001$ . The other main effect of group,  $F(2, 47) = 0.239, p = .789$ , and range-by-group interaction,  $F(2, 47) = 0.605, p = .550$ , were not found to be significant. The ratio of reproduced time in the percentage of respective sample time was indeed in our experiment greater than 1 (1.023) and lower than 1 (0.857) for sub- and suprasedond ranges, respectively. This result was in accordance with the “Vierordt-like effect” (Vierordt, 1868) which proposes that shorter (subsecond) durations are overestimated and longer (suprasedond) ones underestimated.

## Reproduction Error (AE Ratio) and Variability (CV)

Based on the previous result of SSR by fitting participants' reproduced times, we found that elite athletes, independent of their background in fencing or pole-vaulting, were not significantly different in terms of time reproduction. Again, as shown in Figure 3a and 3c, we observed that fencers and pole-vaulters appeared to have extremely similar tendencies of reproduction error and variability along with the increase of sample time. The ANOVA (2 ranges of time  $\times$  3 groups) of AE ratio detected a significant main effect of range of time,  $F(1, 47) = 38.063, p < .001$ , with greater error observed in the subsecond range than in the suprasedond range (mean values were 0.238 and 0.177, respectively). There was also a significant main effect of group,  $F(2, 47) = 8.597, p < .01$ , with both fencers and pole-vaulters making fewer errors than nonathletes,  $p$  values of the two pairs of comparison all less than .005, while there was no difference between the two groups of athletes,  $p = 1.000$  (mean values were 0.195, 0.191, and 0.235 for fencers, pole-vaulters, and nonathletes, respectively). The interaction effect was found to be significant,  $F(2, 47) = 4.741, p < .05$  (see Figure 3b). Post hoc comparisons showed that both fencers and pole-vaulters made fewer errors than nonathletes, particularly in reproducing the subsecond durations,  $p$  values  $< .005$  (mean values were 0.220, 0.208, and 0.285 for fencers, pole-vaulters, and nonathletes, respectively), while no such tendencies were found for the suprasedond time durations,  $p$  values = 1.000 (mean values were 0.170, 0.175, and 0.185 for fencers, pole-vaulters, and nonathletes, respectively). Fencers and nonathletes showed greater error in temporal estimates for subsecond time reproductions compared with suprasedond reproductions ( $p$  values  $< .05$  for fencers and nonathletes and  $p = .09$  for pole-vaulters).

Illustrated in Figure 3c, the ANOVA (2 ranges of time  $\times$  3 groups) of CV detected a significant main effect of range of time,  $F(1, 47) = 128.102, p < .001$ , again with the subsecond range of time revealing greater variability compared with the suprasedond range of time (respective means were 0.236 and 0.163). A significant main effect of group was also found,  $F(2, 47) = 7.710, p < .005$ , with both fencers and pole-vaulters making fewer errors than nonathletes,  $p$  values of the two pairs of comparison all less than .005, while there was no difference between the two groups of athletes,  $p = 1.000$  (mean values were 0.174, 0.169, and 0.211 for fencers, pole-vaulters, and nonathletes, respectively; see Figure 3d). The interaction effect was not significant,  $F(2, 47) = 1.202, p = .310$ .



**Figure 3** — (a) Average reproduction error (AE ratio = absolute error of reproduced time/sample time) in different sample times for fencers, pole-vaulters, and nonathletes. (b) Average reproduction error in the sub- and suprasedond ranges of time for fencers, pole-vaulters, and nonathletes. (c) Average reproduction variability (CV = standard deviation/mean of reproduced time) at different sample times for fencers, pole-vaulters, and nonathletes. (d) Average reproduction variability in the sub- and suprasedond ranges of time for fencers, pole-vaulters, and nonathletes. Error bars indicate standard errors, \* $p < .05$ .

## Discussion

The aim of this study was to investigate whether the long-term training experience of elite athletes has an impact on evaluating the passage of time in a time reproduction task. We tested multiple time durations ranging from 300 to 1,800 ms in 100-ms steps to check whether a single or a two-clock mechanism is applied in sub- and suprasedond ranges of time.

As a general result we found that for all participants, independent of their level of skill, two different clocks for evaluating time below and above a second, respectively, were applied (Buhusi & Meck, 2005). We were able to support this idea by showing a better fit (lower value of SSR) when two separate linear regressions, one for the sub- and the other one for the suprasedond range, were analyzed compared with a single linear regression computed across the entire range of durations tested. The two regressions also showed two different rates of increment. Moreover, the results for reproduction error yield a violation of the first scalar property for time

evaluation (Wearden & Lejeune, 2008), supporting the presence of multiple clocks for evaluating time across multiple scales. Indeed, the idea of having multiple clocks has also been proposed by Kagerer and colleagues (2002) although at different timescales (from 1 to 3 s and from 3.5 to 5.5 s). Here we provide evidence that even for very brief durations, more than one clock is applied. In addition, the results for reproduction variability demonstrate a violation of the second scalar property of time evaluation: As the temporal durations to be reproduced increased, participants' estimation variance (CV) decreased (e.g., Vidalaki, Ho, Bradshaw, & Szabadi, 1999; Wearden & Lejeune, 2008). Taken together, these results suggest that two hypothesized clocks may exist within timescales below and above 1 s.

Although the data of both athletes and nonathletes can be better fitted by two separate regressions, athletes showed higher reproducibility than nonathletes at all the temporal durations tested: Athletes possessed the capacity to keep the reproduced times closer to the target times more consistently compared with nonathletes, even when the task did not specify their domain of expertise and even when time was considered in isolation from space. Moreover, no difference between the two groups of athletes was found. This result implies that high-level sport achievements are obtained by recalibrating and refining athletes' temporal perception independently from their training specificity (closed vs. open skill; Schmidt & Wrisberg, 2008).

It is important to underline that for these clocks to work properly, both accuracy and precision have to be considered, the former to limit deviation from the target time and the latter to minimize the dispersion of estimates around the target (Gibbon et al., 1984; Wearden & Lejeune, 2008). Thus, less error and lower variability in time evaluation imply a better clock system. Remarkably, the athletes' better time estimates were found to be particularly pronounced in the range of time below a second. The ability to reproduce short (subsecond) durations has been related to unconscious and automatic behaviors, triggered by a motor neural loop in particular for SMA, primary motor cortex, and cerebellum (e.g., Buhusi & Meck, 2005; Ivry & Spencer, 2004; Koch et al., 2007). Athletes express higher ability in understanding (Williams & Davids, 1998) and in anticipating (Aglioti et al., 2008; Tomeo, Cesari, Aglioti, & Urgesi, 2012) dynamic events occurring in the space-time domain underpinned by a specific activation of the primary motor cortex (Aglioti et al., 2008). It is important to notice that most sport actions are explosive in nature and are usually performed within a short time window. Therefore, athletes can better recognize and then reproduce time durations particularly within the range of 100 ms. A similar result was found in our recent study (Chen, Pizzolato, & Cesari, 2013) investigating subsecond time estimations of professional pianists.

For the suprasecond range of time, athletes showed the same level of accuracy as nonathletes. Indeed, many daily life activities take place within the range of time from 1 to 2 s. As a result, the ability to reproduce these durations might be easily available for the general population. Nevertheless, athletes presented less variability over trials, implying a better sensory and motor stability as well as timing strategy. In this range of time, temporal processing is considered less automatic while working memory and attention are mostly involved in prefrontal and parietal cortex (e.g., Casini & Ivry, 1999; Lewis & Miall, 2003). Indeed, long-term physical practice can induce adaptive functional and structural changes in the brain such as larger gray matter volumes in frontal and parietal lobe found in skilled golfers (Jäncke et al., 2009) and internationally competitive high-level



professional judo practitioners (Jacini et al., 2009). Physical activity is also found to enhance working memory capacity in both children and young adults (Chaddock et al., 2010; Lambourne, 2006). Moreover, recent studies found that an involvement of parietal regions reduces timing variability in suprasecond time (Vicario et al., 2013; Wiener et al., 2010). To sum up, these findings all support the idea that long-term sporting experience can benefit time estimation (lower variability) in the suprasecond range of time.

In fact, these hypothetical internal clocks can also be damaged as already demonstrated by several neurophysiological studies testing several pathologies (Malapani et al., 1998) or by studies investigating the effect of aging (Rammsayer, 2001). In parallel, cognitive development has also been found to be beneficial in improving the quality of these clocks. For example, Szelag, Kowalska, Rymarczyk, and Pöppel (2002) found that the two older groups of children ages 6–7, 9–10, and 13–14 were more accurate in reproducing temporal durations from 1 to 2.5 s than the youngest group. Whether excellent experience obtained over years of training, such as that possessed by athletes, can recalibrate entirely the sense of time has never been studied. Only a few results suggest that time evaluation may be improved by musical training (Cicchini, Arrighi, Cecchetti, Giusti, & Burr, 2011) or through practice but only by considering a short-term learning period of 5 days (Rammsayer, 1994; Karmarkar & Buonomano, 2003; Perrett, Ruiz, & Mauk, 1993). Here we chose vision as the perceptual modality to be tested because both types of sport considered involve primarily vision for time evaluation: for fencers in anticipating and judging interceptive movements of an opponent and for pole-vaulters in evaluating, for instance, the correct moment of contact for hitting the ground with the pole. In the future auditory stimuli could also be used to test athletes' superiority in the perception of time (Rodger & Craig, 2011).

An important and still unanswered question is whether perceptual and motor systems of time estimation share the same mechanisms and circuits. The results found in this paper suggest that this might be the case. Here we speculate that the better ability expressed by athletes in time evaluation derives from their intense training that specifies time action contexts. Interestingly, motor control researchers involved in understanding action-perception capabilities do not adopt an internal-clock perspective but rather a dynamical system perspective by advancing the idea that time perception is an emergent property within the visuomotor modality (e.g., Bootsma & Van Wieringen, 1990). Several theoretical explanations about timing evaluation refer to intrinsic models (Ivry & Schlerf, 2008) or systems strongly dependent on modality and modality-coordination patterns (Jantzen, Steinberg, & Kelso, 2005) or dependent on a neural network state (e.g., Buonomano, 2007). In these cases, an internal clock does not guide the time evaluation (across different timescales) but the changes in the modalities and their coordinative patterns or the state of the neuronal networks. That is, judging a time duration means being able to recognize these patterns (Buonomano & Laje, 2010). Recently, it has been shown that it is the acquisition of a better control of time that denotes the level of musical performance during learning (Rodger, O'Modhrain, & Craig, 2013). This result has been supported by applying measures derived from "the general tau theory" of temporal guidance of movement (Lee, 1976; Lee et al., 2001). This finding might also sustain our idea that a superior control in time evaluation is a consequence of sport training.

In conclusion, we provide psychophysical data which show the existence of two clocks in estimating temporal durations below and above a second. Elite athletes, as perceptual and motor experts in the time–space domain, even coming from different sports disciplines, demonstrate refined internal clocks compared with nonathletes, especially for very brief durations, because they have a more efficient “automatic” timing system that has been highly developed through sports training. Future research will be performed to test the strength of the two clocks by applying a Bayesian analysis which will consider the nonathletes’ estimates as a prior and the athletes’ estimates as a likelihood function for building up posterior information.

## Acknowledgments

We are grateful to Fabio Pizzolato for his assistance in recruiting the participants and collecting data.

## References

- Aglioti, S.M., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nature Neuroscience*, *11*(9), 1109–1116. [PubMed doi:10.1038/nn.2182](#)
- Allan, L.G. (1998). The influence of the scalar timing model on human timing research. *Behavioural Processes*, *44*, 101–117. [PubMed doi:10.1016/S0376-6357\(98\)00043-6](#)
- Bootsma, R.J., & Van Wieringen, P.C. (1990). Timing an attacking forehand drive in table tennis. *Journal of Experimental Psychology. Human Perception and Performance*, *16*(1), 21–29. [doi:10.1037/0096-1523.16.1.21](#)
- Brown, S.W. (1995). Time, change, and motion: The effects of stimulus movement on temporal perception. *Perception & Psychophysics*, *57*(1), 105–116. [PubMed doi:10.3758/BF03211853](#)
- Buhusi, C.V., & Meck, W.H. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews. Neuroscience*, *6*(10), 755–765. [PubMed doi:10.1038/nrn1764](#)
- Buonomano, D.V. (2007). The biology of time across different scales. *Nature Chemical Biology*, *3*(10), 594–597. [PubMed doi:10.1038/nchembio1007-594](#)
- Buonomano, D.V., & Laje, R. (2010). Population clocks: Motor timing with neural dynamics. *Trends in Cognitive Sciences*, *14*(12), 520–527. [PubMed doi:10.1016/j.tics.2010.09.002](#)
- Casini, L., & Ivry, R.B. (1999). Effects of divided attention on temporal processing in patients with lesions of the cerebellum or frontal lobe. *Neuropsychology*, *13*, 10–21. [PubMed doi:10.1037/0894-4105.13.1.10](#)
- Chaddock, L., Erickson, K.I., Prakash, R.S., Kim, J.S., Voss, M.W., Vanpatter, M., . Kramer, A.F. (2010). A neuroimaging investigation of the association between aerobic fitness, hippocampal volume, and memory performance in preadolescent children. *Brain Research*, *1358*, 172–183. [PubMed doi:10.1016/j.brainres.2010.08.049](#)
- Chen, Y.-H., Pizzolato, F., & Cesari, P. (2013). Observing expertise-related actions leads to perfect time flow estimations. *PLoS ONE*, *8*(2), e55294. [PubMed doi:10.1371/journal.pone.0055294](#)
- Cicchini, G.M., Arrighi, R., Cecchetti, L., Giusti, M., & Burr, D.C. (2012). Optimal encoding of interval timing in expert percussionists. *The Journal of Neuroscience*, *32*, 1056–1060. [PubMed doi:10.1523/JNEUROSCI.3411-11.2012](#)
- Ganslen, R.V. (1961). *Mechanics of the pole vault*. St. Louis, MO: John Swift.
- Gibbon, J., Church, R.M., & Meck, W.H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences*, *423*, 52–77. [PubMed doi:10.1111/j.1749-6632.1984.tb23417.x](#)

- Ivry, R.B. (1996). The representation of temporal information in perception and motor control. *Current Opinion in Neurobiology*, 6, 851–857. PubMed doi:10.1016/S0959-4388(96)80037-7
- Ivry, R.B., & Schlerf, J.E. (2008). Dedicated and intrinsic models of time perception. *Trends in Cognitive Sciences*, 12(7), 273–280. PubMed doi:10.1016/j.tics.2008.04.002
- Ivry, R.B., & Spencer, R.M.C. (2004). The neural representation of time. *Current Opinion in Neurobiology*, 14(2), 225–232. PubMed doi:10.1016/j.conb.2004.03.013
- Jacini, W.F., Cannonieri, G.C., Fernandes, P.T., Bonilha, L., Cendes, F., . . . (2009). Can exercise shape your brain? Cortical differences associated with judo practice. *Journal of Science and Medicine in Sport*, 12, 688–690. PubMed doi:10.1016/j.jsams.2008.11.004
- Jäncke, L., Koeneke, S., Hoppe, A., Rominger, C., & Hänggi, J. (2009). The architecture of the golfer's brain. *PLoS ONE*, 4(3), e4785. PubMed doi:10.1371/journal.pone.0004785
- Jantzen, K.J., Steinberg, F.L., & Kelso, J.A.S. (2005). Functional MRI reveals the existence of modality and coordination-dependent timing networks. *NeuroImage*, 25(4), 1031–1042. PubMed doi:10.1016/j.neuroimage.2004.12.029
- Kagerer, F.A., Wittmann, M., Szelag, E., & Steinbüchel, N.V. (2002). Cortical involvement in temporal reproduction: Evidence for differential roles of the hemispheres. *Neuropsychologia*, 40(3), 357–366. PubMed doi:10.1016/S0028-3932(01)00111-7
- Karmarkar, U.R., & Buonomano, D.V. (2003). Temporal specificity of perceptual learning in an auditory discrimination task. *Learning & Memory (Cold Spring Harbor, N.Y.)*, 10, 141–147. PubMed doi:10.1101/lm.55503
- Koch, G., Oliveri, M., Torriero, S., Salerno, S., Lo Gerfo, E., & Caltagirone, C. (2007). Repetitive TMS of cerebellum interferes with millisecond time processing. *Experimental Brain Research*, 179(2), 291–299. PubMed doi:10.1007/s00221-006-0791-1
- Lambourne, K. (2006). The relationship between working memory capacity and physical activity rates in young adults. *Journal of Sports Science & Medicine*, 5, 149–153. PubMed
- Lee, D.N. (1976). A theory of visual control of braking based on information about time to collision. *Perception*, 5, 437–459. PubMed doi:10.1068/p050437
- Lee, D.N., Georgopoulos, A.P., Clark, M.J.O., Craig, C.M., & Port, N.L. (2001). Guiding contact by coupling the taus of gaps. *Experimental Brain Research*, 139, 151–159. PubMed doi:10.1007/s002210100725
- Lewis, P.A., & Miall, R.C. (2003). Distinct systems for automatic and cognitively controlled time measurement: Evidence from neuroimaging. *Current Opinion in Neurobiology*, 13(2), 250–255. PubMed doi:10.1016/S0959-4388(03)00036-9
- Malapani, C., Rakitin, B., Levy, R., Meck, W.H., Deweer, B., Dubois, B., . . . (1998). Coupled temporal memories in Parkinson's disease: A dopamine-related dysfunction. *Journal of Cognitive Neuroscience*, 10(3), 316–331. PubMed doi:10.1162/089892998562762
- Matell, M.S., King, G.R., & Meck, W.H. (2004). Differential modulation of clock speed by the administration of intermittent versus continuous cocaine. *Behavioral Neuroscience*, 118(1), 150–156. PubMed doi:10.1037/0735-7044.118.1.150
- Mauk, M.D., & Buonomano, D.V. (2004). The neural basis of temporal processing. *Annual Review of Neuroscience*, 27, 307–340. PubMed doi:10.1146/annurev.neuro.27.070203.144247
- McBeath, M.K., Shaffer, D.M., & Kaiser, M.K. (1995). How baseball outfielders determine where to run to catch fly balls. *Science*, 268, 569–573. PubMed doi:10.1126/science.7725104
- Perrett, S.P., Ruiz, B.P., & Mauk, M.D. (1993). Cerebellar cortex lesions disrupt learning-dependent timing of conditioned eyelid responses. *The Journal of Neuroscience*, 13, 1708–1718. PubMed
- Rodger, M.W., & Craig, C.M. (2011). Timing movements to interval durations specified by discrete or continuous sounds. *Experimental Brain Research*, 214, 393–402. PubMed doi:10.1007/s00221-011-2837-2

- Rodger, M.W., O'Modhain, S., & Craig, C.M. (2013). Temporal guidance of musicians' performance movement is an acquired skill. *Experimental Brain Research*, 226, 221–230. [PubMed doi:10.1007/s00221-013-3427-2](#)
- Rammsayer, T.H. (1994). A cognitive-neuroscience approach for elucidation of mechanisms underlying temporal information processing. *The International Journal of Neuroscience*, 77, 61–76. [PubMed doi:10.3109/00207459408986019](#)
- Rammsayer, T.H. (1999). Neuropharmacological evidence for different timing mechanisms in humans. *Quarterly Journal of Experimental Psychology*, 52(3), 273–286. [PubMed](#)
- Rammsayer, T.H. (2001). Ageing and temporal processing of durations within the psychological present. *European Journal of Cognitive Psychology*, 13, 549–565. [doi:10.1080/09541440125713](#)
- Schmidt, R.A., & Wrisberg, C.A. (2008). *Motor learning and performance: A situation-based learning approach* (4th ed.). Champaign, IL: Human Kinetics.
- Szabo, L. (1977). *Fencing and the master*. Budapest, Hungary: Corvina Kiado.
- Szelag, E., Kowalska, J., Rymarczyk, K., & Pöppel, E. (2002). Duration processing in children as determined by time reproduction: Implications for a few seconds temporal window. *Acta Psychologica*, 110, 1–9. [PubMed doi:10.1016/S0001-6918\(01\)00067-1](#)
- Tomeo, E., Cesari, P., Aglioti, S.M., & Urgesi, C. (2012). Fooling the kickers but not the goalkeepers: Behavioral and neurophysiological correlates of fake action detection in soccer. *Cerebral Cortex*.
- Vicario, C.M., Martino, D., Spata, F., Defazio, G., Giacchè, R., . . . (2010). Time processing in children with Tourette's syndrome. *Brain and Cognition*, 73, 28–34. [PubMed doi:10.1016/j.bandc.2010.01.008](#)
- Vicario, C.M., Martino, D., & Koch, G. (2013). Temporal accuracy and variability in the left and right posterior parietal cortex. *Neuroscience*, 245, 121–128. [PubMed doi:10.1016/j.neuroscience.2013.04.041](#)
- Vidalaki, V.N., Ho, M-Y., Bradshaw, C., & Szabadi, E. (1999). Interval timing performance in temporal lobe epilepsy: Differences between patients with left and right hemisphere foci. *Neuropsychologia*, 37, 1061–1070. [PubMed doi:10.1016/S0028-3932\(98\)00155-9](#)
- Vierordt, K. (1868). *Der Zeitsinn nach Versuchen*. Tübingen, Germany: Laupp.
- Wearden, J.H., & Lejeune, H. (2008). Scalar properties in human timing: Conformity and violations. *Quarterly Journal of Experimental Psychology*, 61(4), 569–587. [PubMed doi:10.1080/17470210701282576](#)
- Wei, G., Zhang, Y., Jiang, T., & Luo, J. (2011). Increased cortical thickness in sports experts: A comparison of diving players with the controls. *PLoS ONE*, 6(2), e17112. [PubMed doi:10.1371/journal.pone.0017112](#)
- Wiener, M., Turkeltaub, P., & Coslett, H.B. (2010). The image of time: A voxel-wise meta-analysis. *NeuroImage*, 49(2), 1728–1740. [PubMed doi:10.1016/j.neuroimage.2009.09.064](#)
- Williams, A.M., & Davids, K. (1998). Visual search strategy, selective attention and expertise in soccer. *Research Quarterly for Exercise and Sport*, 69, 111–128. [PubMed doi:10.1080/02701367.1998.10607677](#)