

Lance Armstrong's Era of Performance – Part III: Demonstrating the Post Hoc Fallacy

Hein F.M. Lodewijckx*

Department of Psychology, Open University, Heerlen, The Netherlands

*Corresponding author: Hein.Lodewijckx@ou.nl

Received May 29, 2013; Revised November 10, 2013; Accepted November 15, 2013

Abstract In consequence of USADA's charges, Lance Armstrong conceded he doped during his cycling career. The logic proposed in the *post hoc fallacy* entails that Armstrong's sportive feats are therefore 'caused' by his doping use. This fallacy generalizes to the belief put forward in the doping debate that the progress in speed over time in professional cycling is determined by riders' use of progressively potent doping agents. To examine this fallacy, the current study compared Armstrong's mountain time trial wins, realized in the Tour de France (2001, 2004), to victories demonstrated by riders in similar races uphill in the French race (1958–1996, $N = 17$). The fallacy expects that riders will race faster over time and that Armstrong's achievements will be far superior to other riders. However, if these expectations are disconfirmed the fallacy will be refuted. We developed a climbing index to evaluate riders' km/h performances: $CL_I = (\text{Corrected altitude climb} / \text{Distance trial}) \bullet 100$. Higher values indicate more demanding races. Mediation regression analyses showed that, over time, the trials became less demanding, $b = -.0076$ ($\Delta R^2 = .201$, $p \leq .05$), and that riders raced $b = 0.201$ km/h faster per year ($\Delta R^2 = .234$, $p \leq .05$). The index had a robust influence on riders' speed ($r = -.97$) and they raced $b = -2.302$ km/h slower per unit of the index ($\Delta R^2 = .932$, $p \leq .0001$). The significant mediating influence of the index, $b = 0.175$ km/h ($p \leq .05$), subsequently reduced riders' progress in speed to a nonsignificant $b = 0.026$ km/h per year ($p = .38$, $\Delta R^2 = .003$). Furthermore, Armstrong's performances did not prove to be outliers. Findings invalidate the reasoning employed in the post hoc fallacy, since the CL_I and not the year in which riders competed constitutes the main determinant of riders' performances. They also entail that Armstrong's modern doping agents may not have given him the proposed advantage over his forerunners who won trials before the 1990s, i.e., the years in which these potent aids were not yet rampant in professional road racing.

Keywords: archival records, epo doping, professional road cycling, time trial performance

Cite This Article: Hein F.M. Lodewijckx, "Lance Armstrong's Era of Performance – Part III: Demonstrating the Post Hoc Fallacy." *American Journal of Sports Science and Medicine* 1, no. 4 (2013): 63-70. doi: 10.12691/ajssm-1-4-3.

1. Introduction

A downpour of massive doping schemes has placed the professional cycling world in ill repute the last twenty years [1]. The most recent incident, evoking worldwide commotion, concerns American ex-professional cyclist Lance Armstrong. As a result of USADA's allegations [2] [3], in January 2013 he acknowledged the use of epo, blood transfusions, and testosterone during his active cycling career. These banned doping agents are proposed to powerfully enhance performance, thereby contributing to, or even determining, the superior cycling feats demonstrated by the disputed American racer in his seven Tour de France victories [2,3]. However, we doubt the soundness of this assertion, because we argue that it may constitute an instance of the *post hoc ergo propter hoc fallacy* (translation: after this, therefore because of this [4]). This *post hoc fallacy* reflects the erroneous belief that because there is a temporal sequence in events, one event is the cause of the other. Thus, Armstrong's winning

performances ("after this") are assumed to be caused by his doping use ("because of this"). The current study aims to show that this flawed logic might apply when explaining Armstrong's achievements. To this end, we compared his winning performances, realized in mountain time trials in the Tour de France in 2001 and 2004, to victories demonstrated by riders in similar races uphill in the French race between 1958 and 1996.

1.1 Previous research

Two previous studies contrasted Armstrong's time trial wins, demonstrated on flat and rolling terrain, to victories of other riders in comparable races. Surprisingly, they yielded no solid empirical evidence that his performances were significantly faster than his counterparts. Findings of both studies are summarized in Table 1. The first study [5] compared Armstrong's performances to cyclists, who, from 1934 to 2010, won trials in the three European Grand Tours (Tour de France, Giro d'Italia, and Vuelta a España) facing distances that were equivalent to Armstrong's (50-61 km). The second study [6] contrasted his wins to time

trial victories demonstrated by all former multiple Grand Tour winners (1949-1995; Coppi, Anquetil, Merckx, Hinault, Indurain) as well as all riders who won trials in the three tours from 2006 to 2011. The variation in trial distances in the latter study was much larger (8.2-137 km) than in the former. Both studies assessed riders' mean kilometers per hour (km/h) performances as the dependent variable and they yielded practically identical results on this measure. The first row in Table 1 shows that, across time trials, Armstrong's performances initially were faster than performances of the other riders, explaining 3-6.4% of the variation in speed. Only the first study yielded a significant rider main effect. Importantly, however, after

Table 1. Summary of Findings of Studies Comparing Armstrong's Time Trial Performances to Other Cyclists

Variables	Study 1 (50-61 km) (N = 62)			Study 2 (8.2-137 km) (N = 97)		
	Armstrong	Other riders (1934-2010)	ΔR^2	Armstrong	Multiple winners (1949-2011)	ΔR^2
Unadjusted mean km/h	49.37	44.67	.064*	49.37	46.91	.030 [‡]
Adjusted mean km/h	45.10	45.53	.001	47.49	47.05	.013
Year of competition			.570**			.413**

[‡] $p < .10$; * $p < .05$; ** $p < .001$

1.2. Research Question: Demonstrating the Post Hoc Fallacy

The latter findings imply that the wins of the American ex-cyclist cannot be regarded atypical or 'abnormal.' Besides, the slight amounts of variation explained by the (un)adjusted rider main effects in the two studies suggest that the time trial achievements of all riders are quite comparable and that, therefore, Armstrong did not strongly benefit from his doping use. However, this conclusion may be criticized, since both studies revealed a significant yearly progress in riders' speed. Armstrong won his trials between 1999 and 2005. Hence, the linear relationships could lead one to conclude that Armstrong indeed raced faster than his predecessors and that the doping agents he resorted to might have strongly contributed to these achievements [2,3]. Although we rebutted this criticism extensively in foregoing papers [5,6,7,8], in the current study we will comment once more on this way of circular reasoning, because it might reflect the logic underlying the post hoc fallacy. The fallacy is illustrated in Figure 1. Armstrong's victories can be seen as winning performances (W_P) in Figure 1. He also used modern, ergogenic doping aids, labeled doping use in a certain year (D_Y) in Figure 1. The post hoc fallacy implies that W_P ("after this") is caused by D_Y ("because of this"). This reasoning generalizes to the often heard opinion in discussions about effects of doping, suggesting that the progress in speed over the years in professional road racing (W_P) can be attributed to the use of progressively powerful and advanced banned substances (D_Y) [5-10]. The current study purports to show that this reasoning may be false by examining the relationship between the year in which riders' competed (D_Y) and their winning performances in mountain time trials (W_P). If the relationship between D_Y and W_P proves to be nonexistent, then the logic employed in the post hoc fallacy is refuted.

The foregoing Armstrong studies deliberately assessed his individual time trial achievements as the criterion to appraise his performances over the years, rather than focusing on his final km/h achievements in the seven

statistically adjusting for the strongly confounding influence of the year in which riders competed, in both studies the speed differences between riders disappeared and the rider main effects explained trivial amounts of 0.1-1.3% of the variation in riders' achievements. The positive relationship between year of competition and km/h performances accounted for a significant 41.3-57% of the performance differences between riders, indicating that riders progressively race faster over the years. Both studies further revealed that only one of Armstrong's victories went beyond the very rigorous 68%-CI and none of them surpassed the bandwidth of the 95%-CI.

Tours he won (1999–2005). Several historic studies [7,8], which examined all first-ranking performances of riders in the Tour, Giro, and Vuelta from 1903 to 2011 ($N = 256$), indicated once more that the accomplishments of the American racer were not exceptional. However, these studies may suffer from a methodological flaw. Cyclists' ultimate km/h performances, realized after three weeks of competition in multi-stage cycling races, cannot be considered individual performances, because they may be strongly affected by the (often inestimable) athletic efforts exerted by the bunch of riders participating in the races (the 'peloton'). In individual time trials, riders' efforts are not influenced by these confounding, coordinated peloton forces. In a time trial riders individually race for the fastest time, making it impossible to benefit from the joint labors of cooperating riders in the race through drafting (profiting from the slipstream other riders). Thus, in a time trial riders can only rely on their own athletic capabilities [5,6,11]. Therefore, we maintain that an assessment of these individual performances will increase chances to (indirectly) explore the impact of ergogenic doping agents on Armstrong's cycling feats.

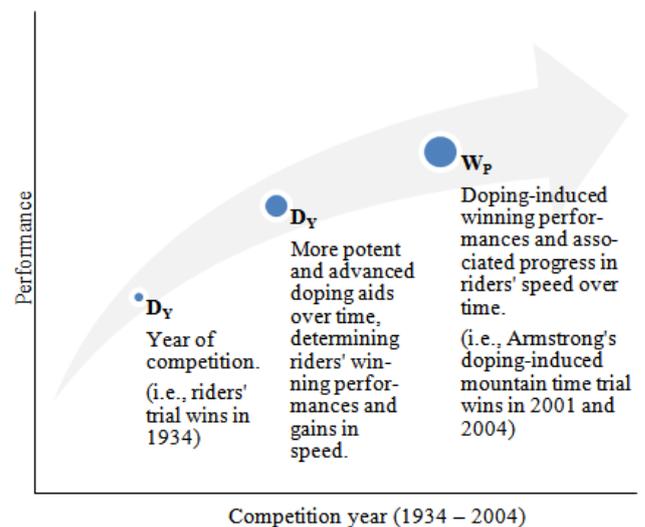


Figure 1. Illustration of the post hoc fallacy to account for riders' winning performances over time

Time trial racing constitutes one of the most demanding disciplines in professional road racing and, within this discipline, mountain time trials are a class on their own [11]. To critically evaluate findings and conclusions pertaining to the two previous Armstrong studies and to investigate the post hoc fallacy, the present research contrasted Armstrong's winning performances in these demanding races to victories of other riders. The logic of the fallacy suggests an increase in riders' speed over time. Moreover, given the proposed powerful ergogenic effects of Armstrong's doping aids [2,3], it further assumes that his km/h performances will be far superior to achievements of the other winners.

2. Method

2.1. Design and Sample

Mountain time trials are rarely scheduled in the three tours [11,12] and the archival records of Magnier and co-workers [12] revealed that all in all nineteen of these trials occurred in the Tour de France in the years following WW II (1958-2004). Records relating to the Giro and Vuelta supplied by [12] were incomplete, forcing us to restrict the examination of our research questions to riders' performances in these nineteen trials. Magnier et al. [12] provided information concerning the winners of the trials, their mean km/h and time performances, as well as the names of the mountains and their altitudes, but they did not give details relating to the slopes of the climbs. We succeeded to retrieve this information from Codifava [13] and cross-checked it with data provided by Van Lonkhuyzen [14] and Ejnes et al. [15]. Table 2 presents descriptive statistics of the variables we measured.

2.2. Measurements

We took notice of the day at which the trials were scheduled during the Tours. The mean *stage number* indicates that, on average, the trials took place at the end of the second week of the three-week races ($M = 14$, $SD = 4$). The *years of competition* ranged from 1958 to 2004. In 1958, famous climber Charly Gaul won the first trial to the top of Mont Ventoux in the Provence. As Table 2 shows, Armstrong won the last two races uphill in 2001 and 2004. The mean *distances* of the trials amounted to $M = 28.85$ km. Note that there is a large between-trial variation in these distances ($SD = 13.14$ km) of which we come to speak below. French five-time Tour winner Bernard Hinault faced the longest and Spanish climber Frederico Bahamontes the shortest trial.

The *altitudes* of the climbs varied between 0.857 km (Cote d'Engins) and 1.909 km (Mont Ventoux) with $M = 1.606$ km ($SD = 0.349$). However, reckoning our research questions, we doubted the validity of these altitudes, because cyclists faced less high elevations. Most of the trials are located at high mountains in the French Alps or Pyrenees, meaning that the riders did not start their races at sea level. However, the altitudes of the climbs are measured from sea level [14]. For instance, it is documented [15] that Charly Gaul in his 1958-trial to Mont Ventoux started his race at Bédoin, a village located at the foot of the climb with an elevation of 327 m. The altitude of Gaul's trial thus amounted to 1.582 km and not

1.909 km. To validly evaluate riders' achievements, we therefore accounted for the elevation at which riders began their trial. After scrutinizing various sources relating to the history of climbs in professional road racing [12,13,14,15], we estimated the *corrected altitudes* of the climbs. They were operationalized as the difference in km between the documented base of the climb (where riders started the race) and the top (where the finish line was drawn). Table 2 indicates that the corrected altitudes are substantially lower (515 m) than the uncorrected heights ($M = 1.091$ km, $SD = 0.292$).

The average *slope* of the climbs is defined as the rise over the run: (rise of the climb / horizontal distance) • 100. The mean slopes amounted to $M = 6\%$ ($SD = 1.37$). Spanish rider and former Tour winner Pedro Delgado as well as Dutch time trial specialist Eric Breukink faced the 'easiest' climbs (Cote d'Engins, $M = 3.3\%$). In 2004, Armstrong faced the steepest climb to the top of l'Alpe d'Huez ($M = 7.8\%$).

As regards the dependent variable, across the sample riders' mean *km/h performances* amounted to $M = 28.87$ ($SD = 5.56$). On average, it took riders approximately one hour to finish the trials ($M = 58:01$, $SD = 18:20$). Note that both performance measures show a large variability, owing to the variation in the distances of the time trials to which we will attend to in the next section.

2.2.1. Climbing Index

Surprisingly, preliminary analyses revealed that larger distances of the trials are strongly associated with faster km/h performances, $r = .83$ ($p \leq .001$). This can be explained by the fact that longer races may involve extended stretches of relatively flat roads, enabling riders to maintain higher speeds compared to trials in which riders instantly have to climb. Moreover, the correlation between the corrected altitude and riders' km/h performances was significant, $r = -.56$ ($p = .01$), whilst the correlation with the uncorrected altitudes was not, $r = -.38$ ($p = .11$). The corrected altitudes thus appear to have better discriminatory value. Additionally, the strong distance-km/h performance relationship entails that we should control for this variable in order to validly address our research questions. Inspired by the research of El Helou and co-workers [9], we therefore developed a *climbing index*, also operationalized as the rise over the run. The rise concerns the corrected altitude in km and the run the total distance of the trial in km and it is expressed in percentages:

Since longer trials involve less climbing kilometers, they are (relatively) less difficult for riders to maintain higher speeds. Therefore, we assume that higher values of the CI_1 designate more demanding trials in terms of riders' instant climbing efforts. Table 2 presents descriptive statistics of the index: $M = 4.36\%$, $SD = 2.26$. The strong interrelationships of the index with other variables make clear that the CI_1 accounts for the influence of the variation in distances of the trials on riders' performances ($r = -.85$, $p \leq .001$) as well as for the influence of the corrected altitudes ($r = .54$, $p \leq .05$) and the slopes of the climbs ($r = .64$, $p \leq .01$). Besides, the index correlates nearly perfectly with riders' speed ($r = -.97$, $p \leq .001$) explaining 94% of the variation between riders. For these reasons, we

chose to attend to our research questions using two variables: The year in which riders competed, permitting

an evaluation of Armstrong's performances in 2001 and 2004, and the CI_1 .

Table 2. Descriptive Statistics of Riders' Performances in Mountain Time Trials in the Tour de France ($N = 19$)

Year	Rider	Climb	Stage	Dis-tance	Alti-tude	Cor. Alti-tude	Mean Slope	CI_1	Mean Km/h	Mean Time	Pred. Km/h	Res. Km/h
1958	Gaul	M. Ventoux	18	21.5	1.909	1.582	7.1	7.36	20.76	1:02:09	21.34	-0.59
1959	Bahamontes	P. de Dome	15	12.5	1.415	1.033	7.5	8.26	20.69	0:36:15	19.28	1.41
1962	Bahamontes	S.bagnères	13	18.5	1.804	1.179	6.3	6.37	23.43	0:47:23	23.71	-0.29
1965	Gimondi	Revard (n)	18	26.9	1.538	1.292	6	4.80	26.97	0:59:50	27.41	-0.43
1977	van Impe	Avoriaz	15	14	1.833	0.873	6	6.21	24.84	0:33:49	24.49	0.35
1978	Zoetemelk	P. de Dome	14	52.5	1.415	1.033	7.5	1.97	36.69	1:25:51	34.27	2.42 ^a
1979	Hinault	S.bagnères	2	23	1.804	1.179	6.3	5.13	26.56	0:53:59	27.03	-0.47
1979	Hinault	Avoriaz	15	54.2	1.833	0.873	6	1.61	34.75	1:33:35	35.12	-0.37
1983	Arroyo	P. de Dome	15	15.6	1.415	1.033	7.5	5.82	25.60	0:35:09	25.54	0.07
1983	van Impe	Avoriaz	19	15	1.833	0.873	6	6.62	22.99	0:40:43	23.69	-0.70
1984	Fignon	Ruchère	16	22	1.042	0.544	4.5	2.47	31.29	0:42:11	33.27	-1.98 ^a
1987	Bernard	M. Ventoux	18	36.5	1.909	1.582	7.1	4.33	27.47	1:19:44	29.06	-1.60 ^a
1988	Delgado	C. d'Engins	13	38	0.857	0.652	3.3	1.72	36.54	1:02:24	35.11	1.42
1989	Rooks	Orc.-Merlette	15	39	1.840	0.709	5.1	1.82	33.01	1:10:42	34.91	-1.81 ^a
1990	Breukink	C. d'Engins	12	33.5	0.857	0.652	3.3	1.95	35.35	0:56:52	34.64	0.71
1994	Ugrumov	Avoriaz	19	47.5	1.833	0.873	6	1.84	34.34	1:22:59	34.99	-0.65
1996	Berzin	V.d'Isère	8	30.5	1.810	0.970	4.2	3.18	35.27	0:51:53	31.95	3.32 ^b
2001	Armstrong	Ch.rousse (s)	11	32	1.721	1.311	6.5	4.10	28.47	1:07:27	29.98	-1.51 ^a
2004	Armstrong	A. d'Huez	16	15.5	1.845	1.127	7.8	7.27	23.44	0:39:41	22.75	0.69
M			14	28.85	1.606	1.019	6.0	4.36	28.87	58:01	28.87	0
(SD)	-	-	(4)	(13.14)	(0.349)	(0.292)	(1.37)	(2.26)	(5.56)	(18:20)	(5.37)	(1.41)

Notes: Distance and (corrected) altitudes are in kilometers. ^a Performances beyond $\pm 68\%$ -CI. ^b Performances beyond $\pm 95\%$ -CI.

2.3. Analyses

We examined our research questions using a mediation regression model (OLS, [16,17]) with riders' mean km/h performances as the criterion and competition year and the CI_1 as predictor variables. The results of these analyses allow an evaluation of Armstrong's doping-induced wins: "Are his performances predicted by competition year and the CI_1 or not, and do they constitute outliers?" If competition year proves to be the main predictor variable and Armstrong's performances are statistical outliers as well, this will render the reasoning underlying the post hoc fallacy plausible. However, if these expectations are disconfirmed, the logic will be disproved. Consistent with previous studies [5,6], we further used the stringent 68%- and 95%-CIs ($\pm 1SD$ or $\pm 2SD$ from the sample mean, respectively) as the criterion to determine outliers. Conventionally, however, performances beyond $\pm 3SD$ are considered outliers [18]. Last, we assessed whether influential cases biased the regression model. Analyses were conducted using IBM-SPSS (v. 20).

3. Results

3.1. Km/h Performances

Following guidelines for mediation analyses provided by [16,17] the regression analyses we conducted, involved four steps. Figure 2 summarizes findings of the analyses. The first step in the analyses showed that the year in which cyclists competed is negatively related to the CI_1 , $b = -0.076$ ($\Delta R^2 = .201$), indicating that the trials became less brutal over time. The second step revealed that competition year is positively related to riders' mean km/h

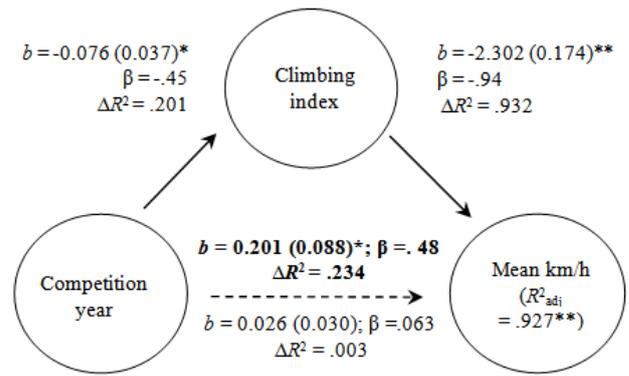
performances, $b = 0.201$ km/h ($\Delta R^2 = .234$). Per year riders race 201 m faster. The third step indicated that the index has a strong negative influence, showing that riders race $b = -2.302$ km/h ($\Delta R^2 = .932$) slower per unit of the index. In the fourth step we simultaneously entered competition year and the index in the regression equation. This step not only allows a test of the mediation effect of the index on the competition year-performance relationship, but also permits an estimation of the degree to which the influence of competition year on riders' achievements is affected by the index. The lower panel in Figure 2 presents the results of the fourth step. The resulting unstandardized $b = 0.026$ km/h ($\Delta R^2 = .003$) indicates that riders raced 26 m faster per year. This relationship is not significant ($p = .38$) and explains 0.3% of the variation in riders' km/h performances. The fourth step further revealed that the CI_1 fully mediated the competition year-performance relationship ($z = 2.10$, $p \leq .05$) and accounted for a substantive part of the variation in this relationship, $b = 0.175$ km/h. Thus, the mediating effect of the index ultimately resulted in the adjusted, nonsignificant influence of competition year on the dependent variable, i.e., $0.201 - 0.175 = 0.026$ km/h. The two variables jointly explain 92.7% of the variation in riders' performances, to which the index contributed by far the most. To conclude, as there is no solid evidence that riders race faster over time, our findings put great pressure on the logic underlying the post hoc fallacy.

3.2. Outliers and normality

The analyses further yielded information concerning riders' predicted and residual performances, which are presented in the last two columns of Table 2. The correlation between the two variables, $r = .00$, indicates a

very good fit of the regression model. Residuals give an indication which performances are not predicted by the variables included in the regression model and, therefore, permit us to evaluate which performances may constitute outliers. Figure 3A and Figure 3B present regression plots of riders' predicted performances with 68%– and 95%–CIs. Table 2 and the figures show that one of Armstrong's wins surpassed the 68%–CI and it concerns his 2001 trial to Chamrousse in the French Alps. However, in this trial he did not perform faster, but 1.51 km/h slower than predicted. In his 2004 trial to l'Alpe d'Huez he raced 690 m faster than predicted. Yet, this performance did not even surpass the 68%–bandwidth. Hence, regarding our research questions, we conclude that the achievements of the American racer do not constitute outliers.

Table 2 and Figure 3A and Figure 3B further indicate that four other riders exceeded the 68%–CI. Three of them performed slower than predicted: French riders Laurent Fignon (1984) and Jeff Bernard (1987) and Dutch cyclist Steven Rooks (1989). In 1978, Dutch rider and former Tour winner Joop Zoetemelk performed faster than predicted on his climb of Puy de Dome in the Massif Central.



* $p \leq .05$; ** $p \leq .001$

Figure 2. Mediation model of variables explaining differences in riders' km/h performances. Presented are unstandardized regression weights (b) and associated standard errors (SE_b) in parentheses and standardized weights (β). As to km/h performances, b and SE_b are in kilometers per hour per year, or in kilometers per hour per unit of the climbing index. The unadjusted relationship between year of competition and km/h performances is in bold type face. The broken arrow indicates a mediated relationship

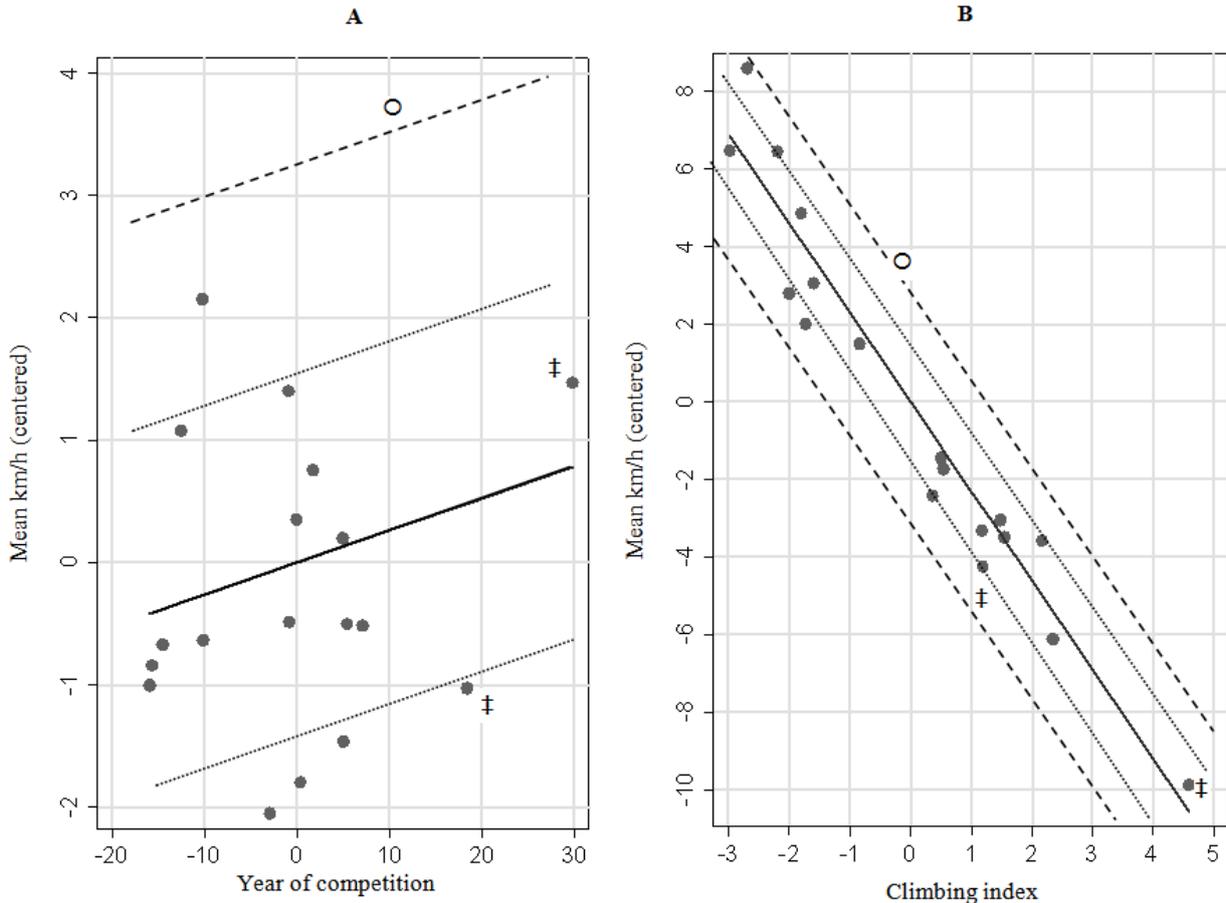


Figure 3. Plots of riders' mean km/h performances regressed on year of competition and the climbing index. Dotted lines indicate the 68%–CI and broken lines the 95%–CI. Open dots (O) present Berzin's performance beyond the 95%–CI and double daggers (‡) Armstrong's performances. Negative values of the centred mean km/h indicate slower performances

Only one of the nineteen cyclists went beyond the 95%–CI in his performance, it concerns Russian rider Yevgeni Berzin in the 1996 trial to Val d'Isère in the Alps. Although we utterly realize that the number of observation is far too low to reliably estimate whether riders' observed, predicted and residual time performances depart from normality, we did evaluate these performances. They all

appeared to be normally distributed (Kolmogorov–Smirnov tests, $z_s \leq 0.71$, $p_s \geq .70$), indicating there are no signs of any 'abnormal' fast or slow performances among the riders, including Armstrong's. To give examples, Figure 4 illustrates the normal probability plots of riders' observed and residual performances.

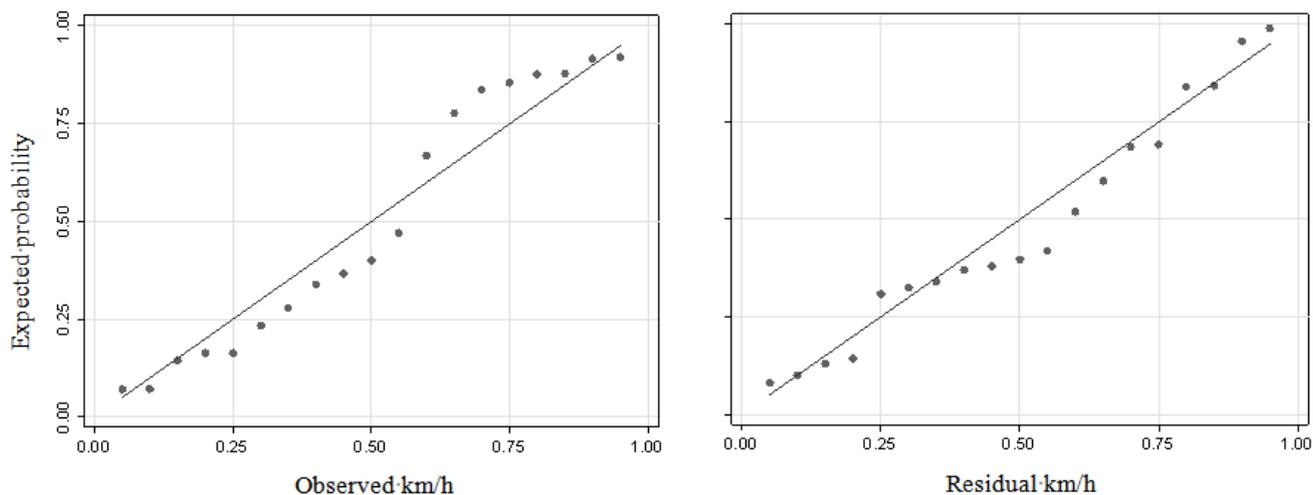


Figure 4. Normal probability plots of riders' observed and residual km/h performances

3.3. Influential Cases

Relative to the other riders, Armstrong's win of the 2004 trial to l'Alpe d'Huez yielded a large leverage value, $h = 0.44$, suggesting that this specific performance might have had an undue influence on the negative slope of the regression line, owing to the fact that his predicted speed strongly deviated from the mean predicted speed. This performance can be seen in Figure 3B (bottom right) and, again, it reveals a comparatively 'slow' achievement of the American racer. To check whether his achievements biased our findings in any way, we conducted auxiliary regression analyses and excluded Armstrong's performances. The results closely matched previous findings. The influence of year of competition ($b = 0.033$ km/h, $p = .49$) and the CI_1 ($b = -2.305$ km/h, $p \leq .001$) slightly departed from the weights presented earlier. The same is true for the total $R^2_{adj} = .928$ ($p \leq .001$). Accordingly, Armstrong's leverage on the overall regression findings appears to be very small. Moreover, we note that it involved a relatively slow and not a conspicuous fast performance, which fell within the bandwidth of the 68%-CI. Importantly, Armstrong's performances did not alter our main finding concerning the post hoc fallacy: Whether or not we included his wins in the analyses, after controlling for the robust effect of the CI_1 , competition year turned out to yield a negligible influence on riders' sportive achievements.

4. Discussion

The logic presented in the post hoc fallacy suggested an increase in speed in riders' mountain time trial performances over the years and, given the proposed powerful ergogenic effects of Armstrong's doping aids, it further assumed that his performances would be superior to achievements of the other winners we included in our sample. Our findings, however, are inconsistent with this logic. After controlling for the influence of the CI_1 on riders' accomplishments, there is no evidence that riders raced significantly faster over time. Moreover, Armstrong's wins in 2001 and 2004 did not appear to be superior, but rather extremely comparable to the

achievements of the other riders. As a matter of fact, his performances came out comparatively slow. What all these findings entail for Armstrong's doping-induced wins will be addressed in later sections, after a discussion of the validity of our study.

4.1. Validity

Although our observations revealed that our regression model is valid and stable, this does not mean to say that there are no factors that may have threatened the internal validity of the study. These factors mainly concern operationalizations and measurements of the variables we used. We already mentioned the problems relating to the altitudes of the climbs. Although one might not suspect this, there is also disagreement about the slopes. For instance, according to some sources the altitude of l'Alpe d'Huez is 1860 m and not 1845 m, and the documented slopes vary between 7.7% and 8.7%. Moreover, there is the additional problem that the corrected altitudes we estimated do not have to agree with the exact spot at which the start and finish lines were drawn in the various time trials. Whenever we encountered such problems, we decided to check at least three different sources [12,13,14,15]. In cases in which two of the three sources showed agreement on a certain value, we included this value in our measurements. If all three sources disagreed, we decided to include the value in between. Besides, the measurement of the distances of the time trials and the related mean km/h and time performances, recorded in the early years of the French race, might also be unreliable. During these years, time for example was sometimes registered by hand [15], and, obviously, this may have consequences for the computation of riders' speed. The same argument holds for the distance of the stages. Thus, in some cases our measurements may be unreliable. However, they only constitute sources of random error; they did not introduce systematic errors in our study. Then again, we have seen that the corrected altitudes predicted riders' km/h performances better than the uncorrected altitudes. Furthermore, the CI_1 , which we based on the corrected altitudes, had a robust influence on riders' performances over time. As a single variable, the index explained 94% ($r = .97$) of the variation in riders' speed, adding validity to our findings and conclusions.

4.2. The Post Hoc Fallacy

This brings us to critically appraise Armstrong's doping-induced wins. Our regression findings designated that, in first instance, there is a significant yearly progress in riders' speed from 1958 to 2004. Since Armstrong won the last two trials in 2001 and 2004, this relationship could lead one to conclude that he indeed raced faster than the other riders did and that the doping agents he used probably contributed to his superior achievements. However, since the CI_I fully mediated the relationship between competition year (D_Y in Figure 1) and riders' performances (W_P), it follows that the (causal?) relationship between the two variables is nonexistent. This means that competition year (with the associated doping use) is irrelevant as an explanatory variable to account for difference in riders' speed, at least where it concerns riders' individual exploits in mountain time trials in the Tour de France. Accordingly, these observations convincingly demonstrate the false way of thinking used in the post hoc fallacy — the main determinant of riders' performances is the CI_I , not the year in which riders won their trial.

After controlling for the mediating influence of the index, findings further revealed that competition year accounted for a minor and nonsignificant 26 m improvement in riders' performances per year, which explained 0.3% of the speed differences between riders. There is the possibility that these minimal improvements may have been influenced by riders' doping use over the years. However, if this assumption is valid, it would imply that Armstrong's advanced doping agents did not give him the advantage over the other riders as suggested by [2,3]. After all, 78% of the riders in our sample demonstrated their feats before the 1990s, that is, in a period in which the use of Hb-augmenting doping aids (epo and blood doping) was not yet rampant in professional road racing [7,8,9,10]. Most of the riders we investigated thus lacked the assumed benefits of the modern ergogenic doping agents, which were available to Armstrong and the other riders in the years of the 'epo epidemic' and thereafter [7,8].

Additionally, it is also conceivable that the effects of doping can be detected in the unexplained amount of variation in riders' winning performances (7.3%), which is not accounted for by competition year or the CI_I . Yet, we argue that this is not a cogent argument either. The residuals appeared to be normally distributed, Armstrong's performances came out comparatively slow, and neither of them surpassed the 95%–CI. Moreover, there are numerous variables which may plausibly account for these unexplained differences, besides doping use. For example, meteorological conditions (wind, heat, rain) during the trials may have strongly influenced riders' speed. Furthermore, the profiles and the irregularity of the climbs vary strongly [15,19]. Compared to l'Alpe d'Huez, Mont Ventoux and Puy de Dome for instance, are known to be much more demanding climbs, characterized by regularly occurring abrupt steep ascents of 12–14% [13]. This impedes riders' efforts to maintain a steady pace while climbing, which may negatively influence their performances. Then again, improvements in the condition of the roads, and technological innovations in the weight and aerodynamics of the bikes and gearing equipment

over the years, may have positively affected riders' achievements. The same argument holds for the profiles and distances of the Tours in which riders competed, which improved over the years, thereby facilitating riders' speed [7,8,11,15].

4.3. Overestimated Effects of Epo?

All these observations lead us to conclude that the performance-enhancing effects of the doping aids Armstrong resorted to might not be as powerful as assumed. This conclusion does not agree with Lundby and Olsen's study [20]. They reviewed results of laboratory studies which assessed the relationship between epo administration and participants' improvements in aerobic exercise capacity, measured by maximum oxygen uptake (VO_{2max}), defined as an estimate of cardio-respiratory, circulatory and muscular fitness that measures the fastest rate at which oxygen can be utilized by the body during intense exercise. They estimated epo effects of 8–12% on exercise capacity. As to blood doping the estimations are 5–10% [21]. Conversely, however, findings of all three Armstrong studies conducted thus far are consistent with other, more critical research which concluded that the effects of Hb-augmenting doping aids on cyclists' endurance performances are overestimated [22,23] and even lack scientific evidence [24]. To critically examine the strength of the epo doping-aerobic performance relationship, Lodewijkx et al. [25] conducted a meta-analysis on findings of seventeen laboratory studies (1991–2010) that hitherto investigated this relationship. The analysis revealed modest effect sizes of the experimental epo vs. control / placebo treatments: $d = 0.41-0.49$, $r = .19-.44$ and $r^2 = .04-.19$. These findings entail that a considerable 81–96% of the differences in performance improvement observed in the studies cannot be explained by epo administration. The largest epo-induced improvement in VO_{2max} found in the analysis equaled an increase in speed of about 1 km/h. Perneger [10] arrives at the same conclusion concerning this increase in speed. However, we emphasize that this slight increase is solely restricted to laboratory situations. It is a well-known fact that such improvements cannot be directly extrapolated to multi-stage cycling races that last three weeks [24,25,26]. All these observations imply that judgments pertaining to the strong ergogenic effects of epo on aerobic exercise capacity might be flawed. In turn, this entails that the relationship between epo doping and performances of cyclists at real contests is strongly overrated too. In our view, this constitutes the most parsimonious explanation for the null results we obtained regarding Armstrong's expected superior time trial performances.

5. Conclusion

Perhaps there remains only one variable which may plausibly explain our observations. It refers to the unique, physical propensities and related time-trial capacities of the very gifted riders we investigated, from Charly Gaul in 1958 to Lance Armstrong in 2004. Our findings illustrate that these capabilities may be underestimated, in particular where it concerns riders who demonstrated their feats in mountain time trials in the early years of the Tour de France. These capabilities make the achievements of all

riders comparable, not their doping use. We also argue that our findings leave hardly any room for rival explanations, such as the use of banned substances, to account for differences in riders' performances over time. Last, our study demonstrates that false, circular logic, as put forward the post hoc fallacy, may hinder the exchange of arguments in the sometimes animated discussions about the (alleged) effects of doping in professional cycling.

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