performance during an Ironman triathlon. *Br J Sports Med.* 2004;38:718–724.
16. Zouhal H, Groussard C, Minter G, et al. Inverse relationship between percentage body weight change and finishing time in 643 forty-two-kilometre marathon runners. *Br J Sports Med.* 2011;45:1101–1105.
17. Hoffman MD, Hew-Butler T, Stuempfle KJ. Exercise-associated hyponatremia and hydration status in 161-km ultramarathoners. *Med Sci Sports Exerc.* 2013;45: 784–791.
18. Miller KC, Mack GW, Knight KL, et al. Three percent hypohydration does not affect threshold frequency of electrically induced cramps. *Med Sci Sports Exerc.* 2010;42:2056–2063.
19. Schwellnus MP, Allie S, Derman W, Collins M. Increased running speed and pre-race muscle damage as risk factors for exercise-associated muscle cramps in a 56 km ultramarathon: a prospective cohort study. *Br J Sports Med.* 2011;45:1132–1136.
20. Hoffman MD, Stuempfle KJ. Muscle cramping during a 161-km ultramarathon: comparison of characteristics of those with and without cramping. *Sports Med Open* 2015;1:8.
21. McKinley MJ, Johnson AK. The physiological regulation of thirst and fluid intake. *News Physiol Sci.* 2004;19:1–6.
22. Verbalis JG. Disorders of body water homeostasis. *Best Pract Res Clin Endocrinol Metab.* 2003;17:471–503.
23. Robertson GL. Abnormalities of thirst regulation. *Kidney Int.* 1984;25:460–469.
24. Engell DB, Maller O, Sawka MN, Francesconi RN, Drolet L, Young AJ. Thirst and fluid intake following graded hypohydration levels in humans. *Physiol Behav.* 1987;40: 229–236.
25. Phillips PA, Bretherton M, Johnston CI, Gray L. Reduced osmotic thirst in healthy elderly men. *Am J Physiol.* 1991; 261(1 Pt 2):R166–R171.
26. Armstrong LE, Maresh CM, Gabaree CV, et al. Thermal and circulatory responses during exercise: effects of hypohydration, dehydration, and water intake. *J Appl Physiol.* 1997;82:2028–2035.
27. Hoffman MD, Stuempfle KJ. Is sodium supplementation necessary to avoid dehydration during prolonged exercise in the heat? *J Strength Cond Res.* 2016;30:615–620.
28. Maresh CM, Gabaree-Boulant CL, Armstrong LE, et al. Effect of hydration status on thirst, drinking, and related hormonal responses during low-intensity exercise in the heat. *J Appl Physiol.* 2004;97:39–44.
29. Berkulo MA, Bol S, Levels K, Lamberts RP, Daanen HA, Noakes TD. Ad-libitum drinking and performance during a 40-km cycling time trial in the heat. *Eur J Sport Sci.* 2016;15:213–220.
30. Daries HN, Noakes TD, Dennis SC. Effect of fluid intake volume on 2-h running performances in a 25 degrees C environment. *Med Sci Sports Exerc.* 2000;32:1783–1789.

COUNTERVIEW: Is Drinking to Thirst Adequate to Appropriately Maintain Hydration Status During Prolonged Endurance Exercise? No

Lawrence E. Armstrong, PhD; Evan C. Johnson, PhD; Michael F. Bergeron, PhD

From the Department of Kinesiology, Human Performance Laboratory, Unit 1110, University of Connecticut, Storrs, CT (Dr Armstrong); the Division of Kinesiology and Health, Human Integrated Physiology Laboratory, University of Wyoming, Laramie, WY (Dr Johnson); and the Youth Sports of the Americas, Birmingham, AL (Dr Bergeron).

No, drinking to thirst (DTT) is not adequate to maintain hydration status or optimal performance during prolonged endurance exercise (which should not be limited to timed events). Enough individual and athletic scenarios exist that preclude the DTT recommendation from being an absolute, unwavering, universally effective guideline suitable for all participants. Importantly, "drinking to thirst" is not equivalent to ad libitum fluid intake,[1] and we are certainly not supporting drinking in excess or "as much as tolerable" during or after exercise. However, optimal fluid intake during any prolonged, repeated, or intermittent physical activity is indeed situation- and individual-specific, which can partially rely on thirst as part of an evidence-informed advanced-planned fluid intake strategy.

To further elucidate, we begin by defining terms and underscoring the key relevant issues. The phrase *appropriately maintain hydration* may be applied in terms of preventing fluid overload, or from the perspective of optimally supporting training-competitive athletic performance. Specific to fluid overload (ie, intake and retention of water exceeding the rate of fluid loss), the concept of DTT (ie, relying solely on one's personal

Drs. Armstrong and Bergeron have no pertinent disclosures or conflicts of interest.

Dr. Johnson discloses that he is currently funded for research by Danone Research, Palaiseau, France.

Corresponding author: Lawrence E. Armstrong, PhD, University of Connecticut, Department of Kinesiology, Human Performance Laboratory, Unit 1110, Storrs, CT 06029-1110 (e-mail: lawrence.armstrong@uconn.edu).

sensation of thirst as the only stimulus or guide to drinking) originated from concerns about exertional hyponatremia during marathons, ultramarathons, and Ironman triathlons lasting longer than 4 hours.[2,3] Subsequently, DTT has been recommended for recreational, sport, and military activities.[4] DTT is 1 of 4 modes of fluid intake including, as well, ad libitum drinking (ie, whenever or in whatever volume desired); an individualized drinking plan (ie, based on past experiences and simulations of a specific sport or activity, including one's measured sweating rate); and programmed drinking (ie, all individuals drink a specified volume per unit of time; volume or rate may be adjusted on the basis of exercise intensity or type of activity).

When considering optimal support of training-competitive athletic performance, it is widely accepted that a measurable degree of hypohydration can reduce strength, power, local muscular endurance, and cardiovascular endurance.[5] Although controlled laboratory and field experiments have demonstrated decrements in prolonged endurance exercise with a minor total body water deficit approximating 1.5% body weight loss,[6–8] a body weight loss of 3% to 4% reduces high-intensity muscular endurance by approximately 10% and muscular strength by approximately 2%.[5] The relevance of these specific body water deficit levels to DTT is that thirst is not recognized until one reaches a body weight loss of 1% to 2%.[9] We recognize that athletes can safely tolerate a small total body water deficit (ie, 2% of body mass loss) by the end of a race or other athletic bout without medical complications or, in some cases, a measurable negative impact on performance. This is especially evident in short-duration or low-intensity bouts of activity. However, an unintended accumulation of total body water deficit can have a measurable negative effect on cardiovascular and thermal strain,[10] exercise-heat tolerance, performance, and safety when the desired pace is forced and intensity is maintained for an extended duration. This is not to say that adequate hydration is sufficient to prevent exertional heat illness.[11] It is simply one of many contributing factors that can mitigate risk, if appropriately addressed.

Although DTT has a logical foundation based on the physiology of thirst,[4] no research has systematically evaluated the effectiveness of DTT to reduce the risk of exertional hyponatremia or to optimize exercise performance. This was acknowledged by the expert participants of the 2015 International Exercise-Associated Hyponatremia Consensus Development Conference,[4] who recommended that future investigations gather evidence with regard to the success of the DTT strategy. Such research ideally uses either a repeated-measures, crossover experimental design in which subjects perform multiple trials (eg, DTT vs ad libitum) or a controlled, group comparison in which one group uses DTT and the other drinks ad libitum. Previous studies that have reported evaluations of runners or cyclists (ie, who claim to "drink to thirst") rarely, if ever, used these experimental designs or recorded ratings of thirst during prolonged endurance exercise. Without ratings of thirst, it is difficult to state with confidence that DTT was the governing sensation behind and prompting the observed drinking behaviors. Importantly, it is unlikely that it can be empirically determined in the field or laboratory whether any athlete is solely relying on 1) inherent thirst alone to avert incurring an undue body water deficit, or 2) a combination of thirst and other influences that underlie ad libitum fluid intake volume or frequency. This challenges the legitimacy of previous arguments[12] and comments[2] that are based on experiments in which fluids were freely available and in which observed practical fluid intake behavior was described as being solely thirst-driven. Further, it is unlikely that laboratory studies (ie, incorporating control of food intake, environment, and exercise) can be extrapolated validly to marathons, ultramarathons, and Ironman triathlons in which athletes routinely consume a variety of foods and sodium, based on individual preferences, during a 4- to 30-hour event.[13,14]

In cases of undue and extraordinary fluid intake, athletes choose to drink far above thirst (eg, between 6 and 12 L during an 89-km ultramarathon[3]), and far above what any individualized hydration plan would have stipulated on the basis of field observations that simulate competition.[15] Although we do not know what prompted such excessive fluid intake in these select instances, we recommend integrating an evidence-informed individualized drinking plan based on personal competitive or training experiences and field measurements,[16] not solely on the subjective sensation of thirst, which has large interindividual variance and is influenced by numerous intrinsic and extrinsic factors.[9,17] In support of this recommendation, no conclusive research evidence exists to explain how different individuals interpret the concept of DTT, or how to accomplish it. In our experience,[1] the concept of DTT is vague and may be easily misinterpreted by athletes (eg, Should I drink so that thirst is always absent? Should I drink only when my sensory perceptions indicate that I am thirsty?). Simply stated, DTT means many things to many people. Researchers also use the terms DTT and ad libitum drinking interchangeably, with no standardization.[1] Further, during endurance cycling exercise lasting 9 hours, thirst ratings and the change of thirst ratings were not statistically correlated with any of the following variables[18]: total fluid intake, preevent body weight, change of body weight, body water balance, height, and ground speed (all R^2 values = 0.00–0.14, all P values > .05). This might be expected because ultraendurance cycling offers continuous and easy access to fluids[18]—that is, competitors carry bottles on their bicycle frame and in jersey pockets, which is a distinctively different level of fluid accessibility and resultant intake behavior compared with endurance running and team sports such as soccer, lacrosse, and American football.

Whether for convenience or because it is seemingly easier to support the argument, most of the discussion to date has focused on athletic endurance activities characterized by a single bout of long-distance running or cycling. Unfortunately, the associated recommendations and unintentional implications are extrapolated to other sports in which fluid or rehydration availability and opportunities are limited or when there are multiple same-day bouts of activity and physical exertion. In these cases, athletes must often recognize and be responsive to both past (ie, just completed, within or between games, matches or training sessions) and future activity that will likely result in a large sweat-induced body water deficit. Moreover, the DTT discussion often focuses on athletes who have "average" sweat rates. This underscores the practical inappropriateness of recommending DTT for individuals who have a high sweat rate[19] and can safely tolerate a more appreciable rate of fluid intake during vigorous activity in the heat.[20] In these scenarios, the longer and more often an individual trains or competes on the same day, the greater the sweat rate and total loss, and the less opportunity there is to recover between and within bouts (eg, time or lack of accessibility), the less effective is the exclusive reliance on DTT.

Notably, we are not arguing or even suggesting that everyone needs to exclusively follow a predetermined individualized rehydration plan during all athletic activities. However, rather than choosing solely DTT or not, we believe that optimal fluid intake during any prolonged or repeated physical activity is situation- and individual-specific, with a proportionate emphasis on either strategy as appropriate. That is, thirst should not be ignored, as it is an innate sensation that directly signals the need for fluid intake. Yet, evidence-informed, preconceived fluid intake strategies that incorporate a personalized, sport-, intensity-, duration-, and environment-specific sweat rate measurement should be given equal consideration when seeking to optimize training and competition drinking practices. Accordingly, our recommended best approach is for athletes to recognize that there is a continuum—one on which thirst alone can be sufficient for certain individuals and scenarios, characterized by varying related combinations of low sweating rate, low exercise intensity, cool environment, and short duration (eg, a recreational runner participating in a local 10k), whereas for other persons and situations, in which sweat rate and total loss are much greater (eg, during an Ironman triathlon or extended multiset competitive tennis match), it is imperative that a greater emphasis be placed on a planned rehydration strategy in combination with DTT.

References

1. Armstrong LE, Johnson EC, Kunces LJ, et al. Drinking to thirst versus drinking ad libitum during road cycling. *J Athl Train.* 2014;49:624–631.
2. Noakes TD. Is drinking to thirst optimum? *Ann Nutr Metab.* 2010;57(suppl 2):9–17.
3. Noakes TD, Goodwin N, Rayner BL, Branken T, Taylor RK. Water intoxication: a possible complication during endurance exercise. *Med Sci Sports Exerc.* 1985;17:370–375.
4. Hew-Butler T, Rosner MH, Fowkes-Godek S, et al. Statement of the Third International Exercise-Associated Hyponatremia Consensus Development Conference, Carlsbad, California, 2015. *Clin J Sport Med.* 2015;25:303–320.
5. Judelson DA, Maresh CM, Anderson JM, et al. Hydration and muscular performance: does fluid balance affect strength, power and high-intensity endurance? *Sports Med.* 2007;37:907–921.
6. Armstrong LE, Costill DL, Fink WJ. Influence of diuretic-induced dehydration on competitive running performance. *Med Sci Sports Exerc.* 1985;17:456–461.
7. Bardis CN, Kavouras SA, Kosti L, Markousi M, Sidossis LS. Mild hypohydration decreases cycling performance in the heat. *Med Sci Sports Exerc.* 2013;45:1782–1789.
8. Bardis CN, Kavouras SA, Arnaoutis G, Panagiotakos DB, Sidossis LS. Mild dehydration and cycling performance during 5-kilometer hill climbing. *J Athl Train.* 2013;48: 741–747.
9. Greenleaf JE. Problem: thirst, drinking behavior, and involuntary dehydration. *Med Sci Sports Exerc.* 1992;24:645–656.
10. Moran DS, Montain SJ, Pandolf KB. Evaluation of different levels of hydration using a new physiological strain index. *Am J Physiol.* 1998;275:R854–R860.
11. Johnson EC, Kavouras SA. Is it possible to be well hydrated and still experience exertional heat illness? In: Sauers EL, Lopez RM, eds. *Quick Questions in Heat-Related Illness and Hydration* Thorofare, NJ: SLACK; 2015:209.
12. Goulet ED. Effect of exercise-induced dehydration on time-trial exercise performance: a meta-analysis. *Br J Sports Med.* 2011;45:1149–1156.
13. Hoffman MD, Hew-Butler T, Stuempfle KJ. Exercise-associated hyponatremia and hydration status in 161-km ultramarathoners. *Med Sci Sports Exerc.* 2013;45:784–791.
14. Hoffman MD, Stuempfle KJ. Sodium supplementation and exercise-associated hyponatremia during prolonged exercise. *Med Sci Sports Exerc.* 2015;47:1781–1787.
15. Casa DJ, Armstrong LE, Hillman SK, et al. National Athletic Trainers' Association position statement: fluid replacement for athletes. *J Athl Train.* 2000;35:212–224.

16. O'Neal EK, Wingo JE, Richardson MT, Leeper JD, Neggers YH, Bishop PA. Half-marathon and full-marathon runners' hydration practices and perceptions. *J Athl Train.* 2011;46:581–591.
17. Rolls BJ. Palatability and fluid intake. In: Marriot B, ed. *Fluid Replacement and Heat Stress.* Washington, DC: National Academy Press; 1993:161.
18. Armstrong LE, Johnson EC, McKenzie AL, Ellis LA, Williamson KH. Ultraendurance cycling in a hot environment: thirst, fluid consumption, and water balance. *J Strength Cond Res.* 2015;29:869–876.
19. Roberts WO, Dorman JC, Bergeron MF. Recurrent heat stroke in a runner: race simulation testing for return-to-activity. *Med Sci Sports Exerc.* 2016;48:785–789.
20. Bergeron MF. Heat cramps: fluid and electrolyte challenges during tennis in the heat. *J Sci Med Sport.* 2003;6:19–27.

REBUTTAL from "Yes"

Martin D. Hoffman, MD; James D. Cotter, PhD; Éric D. Goulet, PhD; Paul B. Laursen, PhD

From the Department of Physical Medicine & Rehabilitation, Department of Veterans Affairs, Northern California Health Care System, and University of California Davis Medical Center, Sacramento, CA (Dr Hoffman); the Exercise and Environmental Physiology, School of Physical Education, Sport and Exercise Sciences, Division of Sciences, University of Otago, Dunedin, New Zealand (Dr Cotter); the Research Centre on Aging, Faculty of Physical Activity Sciences, University of Sherbrooke, Sherbrooke, QC, Quebec, Canada (Dr Goulet); and the High Performance Sport New Zealand, and Sports Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Aukland, Auckland, New Zealand (Dr Laursen).

We are pleased that we seem to be in agreement with Armstrong and colleagues[1] that 1) thirst is a valuable signal for the need for fluid intake, and 2) drinking in excess during or after exercise should not be promoted. It seems that we differ with regard to the extent to which thirst can be relied upon for signaling fluid need and the interpretation of the science on appropriate hydration during exercise. Perhaps most relevant are our differing beliefs about the underlying stimulus for the overhydration resulting in exercise-associated hyponatremia (EAH).

Armstrong and colleagues refer to the 2015 International Exercise-Associated Hyponatremia Consensus statement,[2] of which one of us was an author, and seem to misrepresent some conclusions from that work by suggesting there was uncertainty about the role of thirst in supporting appropriate fluid intake during exercise. In fact, the document is quite clear in noting that drinking to thirst was considered to provide adequate stimulus for preventing performance decrements due to dehydration as well as preventing the development of dilutional EAH, although a few potential exceptions were noted. Perhaps most importantly among the exceptions is the situation where thirst is driven by excessive sodium intake during exercise. Sodium supplementation is a common practice among endurance athletes,[3,4] and there is suggestion that excessive sodium intake can drive thirst, resulting in overhydration and even dilutional EAH[5,6] or pulmonary edema.[7]

It is commonly stated that the sensation of thirst is not recognized until some dehydration has already developed, as was argued by Armstrong and colleagues. Although we accept that there might be some situations involving very high sweat rates when dehydration could precede adequate thirst drive, it is no longer universally accepted that thirst is inadequate to maintain proper hydration during exercise, and concern has been raised that such guidance has been a stimulus for overhydration.[2,8] Interestingly, even the work of Armstrong et al seems to refute the idea that thirst sensation is not elevated until fluid loss has reached 1% to 2% body mass, as they have found thirst with dehydration amounting to less than 1% body mass loss, at least under resting conditions.[9] This supports earlier findings that thirst adequately stimulates drinking before any significant body fluid changes are apparent.[10]

It is also worth noting that both fit and unfit individuals are distinctly thirsty during exercise at mild (∼2%) extents of imposed hypohydration, but fit individuals seem to have greater thirst and greater fluid intake in accordance with their higher requirements during self-regulated exercise for a given level of hypohydration.[11] Fit individuals therefore seem unlikely to be at increased risk of insidious functional dehydration during training or competitive exercise.

We agree with Armstrong and colleagues that appropriate hydration implies avoidance of fluid overload or fluid losses that would impair exercise performance. However, it is not surprising that we disagree on the amount of body mass loss associated with hypohydration and the extent of hypohydration required to impair

The authors have no pertinent disclosures or conflicts of interest.

Corresponding author: Martin D. Hoffman, M.D., Department of Physical Medicine & Rehabilitation (117) Sacramento VA Medical Center 10535 Hospital Way, Sacramento, CA 95655-1200; Phone: 916-843-9027; Fax: 916-843-7345; (e-mail: mdhoffman@ucdavis.edu).