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The Effects of Dehydration on Skill-Based Performance

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Abstract The execution of a skill-based task relies on the collective use of both cognitive and motor skills. Dehydration impairs the ability to maintain thermoregulation and water balance during exercise, particularly in warm conditions, and has been found to inhibit cognitive function and motor skill performance. However, the numerical threshold at which dehydration incurs a decline in cognitive or motor skill performance is widely debated, despite the evidence that performance is impaired after a 1-2% body mass loss. The debate continues due to increasing evidence available from individuals who either possess automaticity of set skills or have acclimatised to dehydration through regular participation in sport, which helps to maintain cognition or motor skill performance. In addition, the use of a variety of pre-protocol methodologies, inconsistent psycho-physiological test batteries and varying athletic behaviours add inherent complexities to determine a general dehydration threshold. Thus, to understand the implications of dehydration on skill-based performance it is important to consider synergistic effects of all of these factors. The present review discusses currently available information on the effects of dehydration on cognitive and motor skills and their contribution to skill-based sporting performance.

Keywords Dehydration, Skill-Based performance, Cognition, Motor-Skill performance

1. Introduction

In euhydration, the normal level of body water is tightly regulated within approximately 0.5% total body water (TBW) and the body's homeostasis regains fluid balance through substantial physiological changes. This consistent effort to maintain water equilibrium occurs on a daily basis, and is greatly influenced by the lifestyle of an individual. A state of mild water imbalance, referred to as hypohydration, is a common situation among athletes in sport and has been shown to be detrimental on a variety of physiological responses [54, 60], starting at a 1% body mass loss (BML) [87]. During sport, athletes often develop progressive dehydration due to multiple reasons. Some athletes may start in a state of dehydration prior to a sporting activity and any drive to increase fluid intake may not adequately replenish TBW. In some cases, the risk for dehydration depends on the demand and nature of the sport, as for example, the opportunity to consume fluid may be accessible only during breaks in play. On the other hand, even if sufficient opportunities for rehydration are made available any delay in thirst drive, which has been documented to occur only after a 2% BML [2], could limit some athletes drive to replenish fluid loss during exercise [44, 70].

When progressive water loss continues to occur, athletes will eventually enter a more severe state of dehydration. This adversely affects both cognition and motor-skill performances during sport; with impairments positively correlated with the severity of dehydration [5, 38]. Therefore, it is important to devise effective hydration strategies to prevent the onset of dehydration. Also, efforts should focus on improving the awareness regarding dehydration, as athletes with higher nutritional knowledge have been demonstrated to ingest higher quantities of fluid [12].

2. Background

Skilled-based performance is the ability to perform a complicated task as a result of the long-term acquisition and development of both motor-skill and cognitive function (e.g. golf swing and basketball three-point throw). Furthermore, a superior skill-based performance has been found to rely on psychomotor function [11]. Multiple studies have identified a decreased skill-based performance during fluid restriction resulting from a 2% BML, compared to euhydration [27-28, 59, 86, 88] with most studies having concentrated on an accuracy assessments as a marker for skill-based performances [5, 26, 87]. Baker et al. (2007) [5] examined the effects of progressive exercise and fluid restriction (1% to 4% BML) to induce dehydration on basketball performance. The study observed a progressive decline in performance with higher subjective feelings of fatigue in correlation with the severity of dehydration. Similarly, tennis players who participated in an intense pre-exercise protocol without fluid replacement prior to skill-based performance assessments reported that even mild dehydration resulted in increased negative subjective feelings, significant decline in

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tennis serve accuracy (30%) and ground stroke accuracy (69%) [23]. Furthermore, Devlin et al. (2001) [26] reported decreased bowling accuracy in elite cricket players when exposed to a state of dehydration of 2.8% BML, however, did not report any changes in bowling velocity. This may not be surprising as dehydration has little effect on activities that involve strength and power generation [41, 96].

A large variety of methodologies have been used to assess the effects of dehydration on skill-based performance [22, 51, 57, 87, 89, 96]. Psychomotor performance of adults following prolonged (i.e. >12 hours) fluid restriction showed poorer cognition when compared to ad-libitum drinking. For example, Szinnai et al. (2005) [90] investigated cognitive performance in 16 participants during progressive fluid restriction found that at 2.5% BML subjective feelings of tiredness, fatigue and rating of perceived exertion increased, and were accompanied by a lower alertness and concentration [90]. Similar findings were also reported by Maughan (2003) [54]: poor cognition performance in terms of reduced alertness and attention, and higher self-reported headaches following prolonged fluid restriction with a 2.86% BML. However, some of these studies were unable to relate the poor cognition with psychomotor performance. An example of this was reported by Petri et al. (2006) [75], where the participants showed poor scoring and solving time following 24 h of fluid restriction, but no change in subjective feelings. Regardless of these inconsistencies, the current literature suggests that prolonged fluid restriction inhibits cognition either through negative subjective feelings; with the length of fluid restriction viewed as an indicator of cognition status in adults [75]. However, the wider effect of poor cognition induced by dehydration on psychomotor skill is still unknown.

Despite extensive research over the past decade, the threshold at which dehydration results in poor sporting performance remains unclear. A threshold of 2% BML as a result of dehydration has been correlated with poor psychomotor and cognitive performance [15, 22, 30, 38, 42]. However, the variety of different methodologies used in previous studies, and the varied requirements of different sports add to the complexity of developing a generalized threshold or cut-off value across sport. For example, in weight category sport such as wrestling the athletes often undergo voluntary dehydration to achieve a required weight. The importance of maintaining hydration for performance is undermined by the aim to achieve a desired body mass, and makes hydration assessment across diverse sports difficult [7, 84, 97]. In addition, many studies investigating the effect of dehydration on performance have not included a sports specific psycho-physiological test battery and may have misinterpreted the importance of psychological status for performance. Overall, it seems unlikely that a universal numerical threshold of dehydration for all sports will be recognized due to the differences seen between sports.

To date, the majority of the current literature concludes that dehydration has adverse effects on cognition and motor skill performance [22, 54, 85, 87]. Because skill-based performance relies on the optimum cognitive and motor skill for optimal performances, it still remains imperative that an athlete maintains a euhydrated status. The present review focuses on the current findings centered on dehydration for skill-based sporting performance. In addition, further considerations for future research are also discussed.

3. Physiological Responses Related to Skill-based Performance

The physiological basis for poor performance from dehydration includes thermoregulation, hyperthermia, cardiovascular strain, increased glycogen utilization and reduced skeletal muscle blood flow [65, 79-80, 99]. Thermoregulatory system controls the ability of the body to adapt to the environment in order to maintain a core temperature around 37°C [55]. Similar to the acceptable range of TBW, there are physiologically accepted temperature limits that the body can tolerate; if exceeded, the body gains or dissipates heat [55]. Consequently, athletes who exercise in warm and humid conditions experience a different physiological adaptation process mainly at the expense of excessive water loss through sweating; a response that momentarily increases the effectiveness of heat dissipation. However, without an adequate fluid replacement strategy athletes would eventually lose a considerable amount of body water and progressively become dehydrated. This may explain the poor psychomotor performances observed in several studies due to >2% BML induced by exercise and heat exposure (Table 1).

Heat dissipation through the water vapor gradient from the skin is higher in dry conditions compared to humid conditions [56]. When executing skills in a warm environment, evaporation (e.g., sweating) becomes the only mechanism for the body to dissipate heat [54] and a high skin to ambient temperature gradient is required to maintain evaporative effectiveness [56, 98]. Unfortunately, in such warm and humid environments the effectiveness of reducing temperature through evaporation is limited due to the lower water vapor gradient. As a result, the higher blood flow to the skin in order to increase heat dissipation only results in the shunting of blood away from the brain and skeletal muscles. In turn, such physiological changes are consistent with increases in rating of fatigue [56] and can contribute to the onset of dehydration and its associated negative impacts on skill-based performance [23-24, 35-36, 67].

A high environmental humidity and temperature directly reduces the body's ability to maintain thermoregulation [54, 56] with this effect amplified when exercising in such conditions [36-37]. Voluntary fatigue occurs at approximately 40°C [62, 68], and sports performance is directly enhanced by ambient temperature [71], maintained pre-exercise core temperature [35] and hydration status [43, 48]. These findings have led to studies of pre-cooling as a method to improve performance [35].

Further research has also focused on carbohydrate ingestion as an effective fluid replacement strategy for maintaining skill-based performance at different environmental temperatures [31, 81, 89]. This is because skill-based tasks involve complex brain activities that require higher concentrations of glucose than the normal activities [45]. Several studies have shown better motor-skill with the endogenous availability of glucose compared to a non-energy placebo in a range of temperatures [5, 9, 89, 92]; with similar results also observed for cognitive performance [22, 89] and in exercise induced fatigue [19]. Collectively, these studies suggest that performance of tasks that involve higher cognitive demands and multi-joint coordinated movements (e.g., golf swing, archery) benefit from glucose ingestion; however, evidence for improved skill-based performance for glucose-based drinks over water are inconsistent [5, 12, 89].

Research has used different methods to induce dehydration in various settings such as prolonged water restriction [90], exercise [4], or diuretic use [96]. Regardless of the different methods used, dehydration has shown to cause cardiovascular stress (e.g. increased blood osmolality). For example, dehydration induced by low to moderate intensity exercise in temperate environments increased heart rate compared to hydrated subjects [25, 76]. As sensations of thirst may be delayed until > 2% BML [2], the athletes may be unaware of their hydration status and this may provide a possible explanation for the higher associated cardiovascular stress [35, 76, 79]. Additionally, the body can store fluid within intracellular or extracellular compartments. Plasma accounts for up to 20% of extracellular fluid, and it predominantly contributes to sweating. During exercise, the majority of body water is lost through increased sweat production and results in reduced blood volume, increased plasma osmolality and higher heart rates [4, 76]. This increased cardiovascular stress may cause negative effects on skill-based performance as studies have identified lower heart rates along with better skill-based actions in elite athletes [10, 18, 61] and with the better performances correlated with lower cardiovascular stress [5, 74, 87].

4. Cognitive Responses Related to Skill-based Performance

The complex combination of physiological processes described in the previous section may help explain the decline in skill-based performance in dehydration. However, the sole focus on physiological explanation may underestimate the effects of dehydration on skill-based performance [65]. The association between poor cognitive function and dehydration has been well documented (Table 2); negative changes in emotions detected prior to any physiological adaptations in response to dehydration [30, 38, 90]. Ganio et al. (2011) [32] tested the ability to maintain euhydration during exercise in 26 adults who were on diuretics or non-diuretic placebo in temperate conditions (27ºC) [32]. The study reported increased tension and fatigue were reported when subjects were dehydrated (> 1% BML) compared to the state of euhydration (i.e. < 1% BML). These findings suggest that fluid restriction heightens the negative subjective feelings such a tiredness, fatigue, and lower concentration and alertness associated with poor skill-based performance.

The benefit of improving skill-based performance through automaticity is never more apparent than when one considers the role of attention while learning performance related skills [1]. The use of attention as a strategy for learning skill-based tasks has been well documented [8, 40, 73, 77, 82]. These strategies are based on the use of either external (e.g., hand placement) or internal (e.g. ball flight) attention focus. Skilled players who possess automaticity (e.g. golf swing) have been shown to benefit from the use of external attention [8, 40], whereas inexperienced athletes have only reported improved performance when implementing either multiple external attention cues [82] or in combination with physical skills [58]. According to Wulf et al. (2001) [100] based on the constrained action hypothesis, external attention allows freedom for automaticity with the lower cognitive demands in skilled performers, while emphasizing the benefits of using external attention interventions on improved performance. Consequently, athletes with consistently better skill-based performance exhibit superior use of multiple cognitive skills, including concentration, attention, mental preparation, and automaticity, and fewer negative cues [93-94]. To highlight this point, Hayslip et al. (2010) [41] conducted a performance, anxiety and cognition-coping survey of 1334 amateur golfers and reported significantly greater use of cognition skills (e.g., goal-setting, imagery, automaticity) by skilled golfers compared to their less skilled counterparts. Also, skilled players reported fewer negative cues while less skilled players had a tendency to project attention towards negative cues to allow a drift in attention. The above study also identified commitment and automaticity as traits associated with skill-based golf performance (e.g., golf swing). Thus, automaticity is an important cognitive trait in skilled performance, which may reduce external stress caused by the variety of dynamic cognitive demands and distractions often experienced during competition [91] and other cofounders to include personal achievement, rewards, and peers [17, 34, 60, 93]. This relationship has led coaches, players and researchers to recognize the value of coping strategies to improve attention and concentration in skill-based sport. For example, pre-routines which reflect well developed cognition strategies [20] have been shown to increase adherence, attention and fewer negative cues, even in inexperienced golf players [58], and have contributed to better success when performing repeated actions over a long period of time [21, 49].

The relationship between dehydration and skill-based performance has become largely equivocal. This is due to several studies demonstrating that dehydration inhibits cognition (Table 2) resulting in tiredness and poor short-term memory, attention, and concentration [3, 14-15, 85, 90]. Many of these studies have documented poor cognition following prolonged episodes of fluid restriction [50, 85, 90], exposure to exercise [22, 69] and heat [38-39, 56]. Thus, these studies demonstrate the potential negative effects of dehydration on the cognition required for learning skill-based tasks. Recently, Smith et al. (2012) [87] documented the impact of mild dehydration (1.7% BML) on cognition in low handicap golfers. The study identified that dehydration (1.5 ± 0.5% BML) significantly impaired cognition and skill-based golf performance through reducing shot distance ($p < 0.001$), target accuracy ($p < 0.001$) and distance judgment ($p < 0.001$) compared to euhydration in low handicap players [87]. An explanation for the poor performances in dehydration could be the increased subjective fatigue and perception of effort reported when participating in golf [47]. Furthermore, when considering the combined effect of negative emotions and fatigue ratings associated with dehydration, it is unsurprising that previous reports have shown poor performances during multi-joint psychomotor actions in dehydrated athletes [33, 78, 89, 95]. These studies collectively suggest that cognition decline due to dehydration can inhibit the ability to execute skill-based tasks.

On the other hand, researchers have reported minimal effect on cognition as a result of progressive dehydration of >2% BML induced by exercise and water restriction [22, 75]. A few studies have also reported that trained individuals with developed cognitive function (e.g., concentration and determination) are able to maintain cognition even in a dehydrated state [13, 46, 83, 88] and that performance is not improved as a result of maintaining hydration [64]. Carvalho et al. (2011) [12] reported a sustained level of skill-based performance in adolescent basketball players despite significant increases in BML and subjective feelings of exertion as a result of non-fluid ingestion compared to water and 8% carbohydrate-electrolyte solution. These studies suggest that athletes who are acclimatized to the demands of their sport and frequently become dehydrated during performance are able to sustain both cognition and skill-based performance. This has led to many researchers to accept the "*Thirst Response Model*" [64, 66, 67]. The above model suggests that a thirst response is initiated as a result of the body's detection of physiological changes (e.g. blood viscosity), and that the body uses this response as a cue to increase fluid intake. However, such a model may only be applicable to acclimatized athletes in certain sports. For example, some of the studies that have proposed the thirst response model have focused either on weight category sports where individuals are accustomed to severe voluntary dehydration [46], or in sports that require a lower cognitive function (e.g., long distance running or cycling).

In addition, the lack of adequate sports-specific cognitive test batteries may have underestimated the impact of dehydration on cognition. This limitation partly may explain the reduced understanding of automaticity for performance reported in the aforementioned studies. Thus, for sports that require high cogitative-function, a model based on an individual's responses to their own thirst may not be appropriate [16]. Alternatively, Barr's workspace theory is based on the hypothesis that cognition has a limited processing capacity and that negative cues, such as subjective thirst associated with dehydration, could compete for executive space [6]. D'Anci et al. (2009) [22] found that dehydration induced through water restriction and exercise exposure reported higher thirst, negative mood ratings and poor processing speeds compared to euhydration. Therefore, Barr's workspace theory could explain this phenomenon. In addition, the consistent execution of complex tasks has also been shown to require higher cognitive performance [45]. Therefore, the ability to respond to a thirst response could hinder performance as it may reduce executive cognitive space and function. This could result in a scenario whereby higher negative cues (e.g., thirst drive) reported during dehydration [53] could reduce the attention and concentration needed to execute skill-based performance.

Table 1. Effects of Induced Dehydration on Skill-based Performance

Reference	Performance	Dehydration Status/Method	Outcome
Epstein et al. (1980)	Skilled-based performance	2.5% BML	Reduced accuracy and speed of complex tasks.
Derave et al. (1998)	Postural stability	2.7% BML & 3% BML	Reduced postural stability
Baker et al. (2007)	Basketball	1 – 4% BML	Progressively reduced accuracy, shooting time and number of shots.
Carrasco (2008)	Surfing Performance	3.9% BML	20.3% performance reduction
Smith et al. (2012)	Golf accuracy and distance judgment	1.45% BML	Reduced ball carry, shot accuracy and distance judgment

BML: body mass loss

Table 2. Influence of Dehydration on Cognition

Reference	Dehydration	Cognitive Performance	
		Increase	Decrease
Gopinathan et al. (1988)	1,2,3 & 4 % BML	-	Short-term memory
Cian et al. (2000)	2.8 % BML	Fatigue	Short-term memory
Shirreffs et al. (2004)	2.7 % BML	Reports of headache	Concentration & alertness
Szinnai et al. (2005)	2.6 % BML	Tiredness & effort	Alertness
Petri et al. (2006)	-	-	Solving time, objective Processing
Carrasco (2008)	3.9 % BML	-	Short-term memory, attention, speed
Patel et al. (2007)	2.5 % BML	Dizziness, headache & fatigue	Concentration
D'Anci et al. (2009)	2.0 % BML	Thirst ratings	Attention & mood
Ganio et al. (2011)	1.0 % BML	Anxiety, tension & fatigue	Working memory Response
Smith et al. (2012)	2.0 % BML	Distance judgment	Accuracy

% BML: percentage body mass loss

5. Methodological Issues Related to Skill-Based Performance

A number of researchers have used a combination of fluid restriction and exercise to induce dehydration and to investigate the effects of dehydration on skill-based performance [23, 26, 52, 78, 87, 95]. However, the use of a variety of different methodologies may highlight difficulties in comparing evidence on the effect of dehydration in sport. Therefore, it is important to consider the different methodologies used in the current literature before concluding any negative effect of dehydration on sports performance. For instance, the inclusion of both exercise combined with fluid restriction in order to inhibit dehydration, may confound the cause and effect analysis and highlight fluid restriction as a single factor affecting skill-based performance [22], and that the poorer performances observed may have come from either the use of exercise, prolonged fluid restriction, or a combination of both. This must be considered while designing a sports specific method to investigate skill-based performance as a function of dehydration.

Although previous research using prolonged fluid restriction prior to performance has highlighted the importance of regular hydration strategies during sport, caution must be exercised before applying such findings to a sports setting; this is because fluid restriction over long periods prior to performance does not reflect normal preparation [65, 85]. Instead, researchers need to consider the value of pre-dehydration (>12 h) methods within their sport. This is because any increases in negative cues may result from the use of a pre-dehydration protocol rather than dehydration during skill-based performance. This provides the reason for why the validity of such methodologies used to induce dehydration has been debated as most study designs for inducing dehydration have included pre-protocol heat and exercise [38], diuretic use [63, 96] or progressive voluntary dehydration [90]. Previous studies have demonstrated that pre-dehydration protocols tend to reduce plasma osmolality, which is detected by the brain and could lead to under performance through pacing (i.e., when an individual subconsciously reduces his/her performance due to inappropriate preparation) [29]. Therefore, when interpreting results of research studies, coaches and athletes need to be aware of the implications of pre-study designs to induced dehydration and the effect they may have on the subsequent performance. Another limitation of many existing studies is the lack of adequate psycho-physiological measure to assess skilled-based performance specific to a sport as a result of dehydration. McGregor et al. (1999) [59] and Edwards et al. (2007) [29] reported maintenance of concentration level but impaired psychomotor ability during skill-based performance (e.g., dribbling) in dehydrated compared to euhydrated soccer players. The above finding suggests that concentration was not impaired while dehydrated and that the player's level of concentration had a limited influence on soccer performance. However, neither of these studies used a multi-cognitive or sports-specific cognitive test battery and therefore could have underestimated sports-specific impairment in cognition. Future studies that include a full cognitive test battery are needed to further understand the broad range of cognition associated with specific sports. Moreover, inclusion of a thorough psycho-physiological test battery to evaluate the decline in performance with dehydration would help minimise the validity issues that confound the effects of dehydration on sports performance.

The majority of current literature shows that dehydration has adverse effects on skill-based performance with a number of reasons proposed, however, the inconsistent trend between poorer cognition and motor performance prevents a conclusive direct cause and effect analysis of dehydration on skill-based performances. Nevertheless, dehydration has shown to result in the decline of these performance subscales, which should be considered independently as a potential inhibition on skill-based performance.

6. Conclusions

In conclusion, dehydration has been shown to result in poorer cognitive function and motor skill that contribute towards a poorer skill-based performance. Physiological responses such as hyperthermia, reduced skin blood flow, and cardiovascular strain are associated with dehydration and provide a physiological explanation for diminished sports performance [65]. However, the frequently reported decrease in cognitive function suggests that the effect of dehydration goes beyond a physiological explanation. Both cognitive function and motor skill are subscales of skill-based performance, and their inhibition by dehydration provides some explanation for the poorer skill-based performance of dehydration versus hydrated athletes reported in previous studies [5, 87]. On the other hand, athletes with high automaticity of skill and those who are frequently acclimatized to dehydration may be able to sustain cognitive-function, motor skill, and skill-based performance. Coaches and athletes must evaluate the relevance of methodologies used in previous studies before drawing conclusions about the effects of dehydration on skill-based performance related to their own sport. Methodologies that include prolonged fluid restriction, pre-exercise protocols or use of diuretics all have their own validity issues that must be considered when interpreting the effects of dehydration on skill-based performance. When trying to identify hydration strategies that will maintain skill-based performance further considerations should include the demands of the specific sport, the environment in which the sport is played, and athletic behaviors such as voluntary dehydration. Furthermore, to better understand the effects of dehydration on related skill-based performance further studies should include adequate psycho-physiological test batteries that cover all of the attributes required for consistent performance.

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