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Keeping an eye on noisy movements: On different approaches to perceptual-motor skill research and training

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Key points

- Evidence indicates that variability in movement control facilitates adaptation during both learning and performance, meaning that it is detrimental for all learners to aim to replicate a universal movement pattern.
- Gaze behaviour studies have proposed the importance of universal 'optimal' gaze patterns, for all performers in a given task, irrespective of stage of learning.
- New lines of inquiry aimed at new approaches to the role of variability in gaze behaviour may lead to understanding of this facet of perceptual-motor skill and its acquisition.

Abstract

Contemporary theorising on the complementary nature of perception and action in expert performance has led to the emergence of different emphases in studying movement coordination and gaze behaviour. On the one hand, coordination research has examined the role that variability plays in movement control, evidencing that variability facilitates individualised adaptations during both learning and performance. On the other hand, and at odds with this principle, the majority of gaze behaviour studies have tended to average data over participants and trials, proposing the importance of universal 'optimal' gaze patterns in a given task, for all performers, irrespective of stage of learning. In this article, new lines of inquiry are considered with the aim of reconciling these two distinct approaches. The role that inter- and intra-individual variability may play in gaze behaviours is considered, before suggesting directions for future research.

1. Introduction

Despite emphasis in contemporary theory on the complementary nature of perception-action in expert behaviour [1, 2], different approaches to perceptual-motor research have emerged. For example, one branch of coordination research is characterised by studies that have analysed the variability between- and within-individuals [3], while in one facet of perceptual skill research, gaze behaviour studies have tended not to examine performance variability, with data averaged over participants and trials [4]. Moreover, current approaches to training gaze patterns have emphasised investigation of universal 'optimal' search strategies for a given task [5, 6]. In contrast, a number of coordination researchers have proposed a requirement to move away from 'one-size fits all' interventions towards understanding of how individualised movement patterns emerge for a given task [7]. Thus, at face value, there are two different conceptualisations of expertise and learning in the perceptual-motor literature. With the aim of considering whether the two approaches can be reconciled, we reflect on the role that inter- and intra-individual variability may play in gaze behaviour before offering considerations for future research. We begin by overviewing some key principles that have emerged in gaze behaviour research before considering lessons that could be learned from the coordination literature.

2. The search for optimal gaze behaviour

For some time it has been known that accurate and skilful behaviour requires the education of attention towards task relevant information [8]. Researchers in the sport expertise literature have tended to utilise gaze measures in order to identify the locations of information pick-up. Dependent measures include the locations and durations of fixations that offer understanding of the spatiotemporal distribution of gaze patterns [4]. There is a clear trend across gaze behaviour studies to average data across participants and trials. In an oftencited example, Savelsbergh and colleagues [9] measured gaze behaviours of semi-professional and novice goalkeepers seeking to predict the direction of penalty kicks presented via video footage. On average, the semi-professionals and novices attended to different locations during the anticipation task, with the former fixating fewer locations than novices. Novices spent more time fixating trunk, arm, and hip regions of the penalty taker. In contrast, semi-professionals spent more time fixating the kicking leg, non-kicking leg, and ball regions. Supporting these findings, different anticipation studies highlight that, on average, skilled performers fixate different – and typically fewer – gaze locations for a longer duration in comparison with novices [10-12].

One particular gaze dependent variable that has received noticeable attention in the literature is *quiet eye* (QE) [13]. QE is defined as the "final fixation or tracking gaze that is located on a specific location or object in the visuomotor workspace…[that] occurs prior to the final movement of the task… the quiet eye may be viewed as an objective measure of optimal perceptual-motor coordination" [14]. Vickers introduced the QE measure during an examination of basketball performance [13]. On average, expert players were found to use longer QE durations in comparison with near-experts (972 vs. 357 ms) during successful free-throws. Two-decades of research has examined QE across a range of sport situations, most of which have been focused on sport aiming tasks, although there are also studies conducted in non-sport domains [15, 16].

A number of interpretations of why QE may contribute towards successful performance exist, including information processing [17], movement programming [13], and prospective control [18] accounts. Despite variations in interpretation, a noticeable feature of QE research is that data have almost exclusively been reported as a mean duration of group level performance, averaged across participants. Most crucially, QE, like other perspectives in the gaze behaviour literature, implicitly emphasises that expert performance may be a consequence of the acquisition of one 'optimal' gaze pattern for a given task, with the dedicated aim of research being to confirm the existence of this universal gaze pattern [19]. The implication of this body of work for learning is that, in order to perform successfully, participants must converge upon an optimal gaze behaviour (focusing on duration of QE) in order to achieve successful performance outcomes in a given task [20]. Indeed, a number of promising learning studies demonstrate that observation and replication of a skilled individual's gaze pattern can have a positive impact on novice performance [5, 15]. However, findings from other learning studies in perceptual skill research have reported that less-skilled participants fail to replicate the gaze patterns of skilled performers [6] or that observation of expert gaze patterns fails to enhance learning in novices [21].

Comparable to the perspective outlined in the sport expertise literature, the historical preference in the broader visual cognition research has often been to analyse data at the group level, with evidence indicating that people appear to converge on the same gaze patterns during the completion of both every-day (e.g., making a cup of tea) and laboratory-based tasks [22, 23]. However, recent laboratory-based studies that have presented complex displays to participants, such as multiple-object tracking research, have revealed that different gaze behaviours are used to achieve performance outcomes in the same task [24, 25]. Thus, it has been argued that calculation of the group average may misrepresent individual participant data, limiting understanding of cognitive and behavioural strategies [26]. Moreover, there is a suggestion that the preference to analyse gaze data at the level of a group average implies that gaze patterns either side of a mean value reflect *noise* (dysfunctional variability) in the data [27]. Indeed, gaze behaviour data, which comprise fixations of longer durations on fewer locations, are often labelled as being more efficient, regardless of task constraints and individual differences [28]. A central consideration that needs addressing, therefore, is whether variation in gaze patterns – durations and locations of gaze that fall either side of the mean for a group – between- and within-individuals is inefficient *noise* or an important aspect of adaptive performance. In the development literature, evidence indicates that exploratory (variable) behaviours play a fundamental role in the learning process [29]. Thus, it is possible that an over-reliance on average gaze data may mask understanding of the individual adaptations that are present in learning [30] and development [29].

3. Movement coordination and variability: the role of noise

An important theme in human movement coordination research in the last two or three decades has been the study of variability and its role in motor control [31-33]. Historically, some scientists have considered movement variability as noise – akin to the mechanical noise that exists in engineering control systems – and thus damaging to performance [34]. Despite such suggestions, it is increasingly acknowledged that it is misleading to portray biological systems as *optimising* systems. That is, biological organisms – unlike engineering systems – exploit "good enough" solutions during task achievement [35]. In sport, research evidence demonstrates that when a person attempts the same task on multiple occasions, the movement dynamics differ from one performance to the next [31]. Moreover, when movements are compared across participants, findings indicate demonstrable variation between the coordination patterns utilised by different athletes to achieve the same outcome [36]. Such evidence has, therefore, been interpreted to argue that variability plays a necessary role in performance achievement and even injury prevention [37].

Much of the research concerning the role of variability in motor coordination has origins in Bernstein's [38] multiple degrees of freedom (*df*) problem, which describes the acquisition of coordination as a process that controls redundancy in movement. In the process of learning to kick a football, for example, in the kinematic chain of the action, there are many elements that contribute to movement execution that need to be coordinated together [39]. A consequence of *df* is the observation that practice is a form of "repetition without repetition" [38]. Variable coordination tendencies have been observed in the learning and control of movements where one may expect to observe a common optimal movement pattern [40]. Pertinent to such findings is the acknowledgment that attempts to train putative optimal movement patterns typically fail [41]. As such, skilled performance is geared toward outcome achievement rather than the process of how to achieve. To this end, motor learning perspectives have increasingly emphasised the acquisition of variable coordination patterns, predicated on contextual performance effects (e.g., fatigue, emotions, expectations) as opposed to *a priori* defined optimal movement models [42, 43].

During learning and development, variability has been shown to support the exploration and search for adaptive movement solutions in different conditions [29, 30]. Müller and Sternad [33] proposed that skilled performance is associated with learners discovering solutions that have a tolerance for the variability that is inherent within the task and coordination *df*. Within so-called 'solution manifolds' small fluctuations (variations) alter the outcome only minimally. Large solution manifolds have more tolerance for different movement solutions. For example, different kicking techniques can be used when learning to achieve a successful passing outcome in football [39]. In contrast, smaller manifolds may only allow subtle modifications. The implication is that if movement variability is present during learning it allows the learner to search, find, and subsequently refine appropriate solution manifolds for different performance contexts. Hence, the utilisation of different techniques appears necessary to facilitate adaption to the different levels of complexity encountered during sport [31].

The utilisation of equally successful, yet structurally different, movement patterns in coordination has been interpreted as evidence of degeneracy in perceptual-motor control [39].

Degeneracy is technically defined as ‘the ability of elements that are structurally different to perform the same function or yield the same output’ [44]. Like other theories that have recognised the importance of neural plasticity in the organisation of brain-body [45], degeneracy is considered an evolutionary solution that offers reduction in repetition, fatigue and degenerative stress on organs and body structures [46]. Hypothetically speaking, in a non-degenerate movement system, if an athlete used a technique that deviated from the optimal pattern due to fatigue, one would expect to see a decrease in performance. In contrast, evidence shows that skilled water polo players switch between different shooting techniques under different levels of fatigue without detriment to success [47]. In this regard, degeneracy is thought to be an essential feature of learning, skilled behaviour, and recovery from injury [48].

4. Considering variability in gaze behaviour

Our initial overview has identified two different approaches to the study of perceptual-motor skill. On the one hand, evidence indicates that variability in movement organisation facilitates adaptation during both learning and performance, meaning that it is detrimental for all learners to aim to replicate the same movement pattern. On the other hand, and at odds with this principle, many gaze behaviour studies have proposed the importance of the same 'optimal' gaze patterns, for all performers in a given task, irrespective of stage of learning. Here, we consider whether new lines of inquiry aimed at advancing approaches to interpreting the role of variability in gaze behaviour may lead to a more comprehensive understanding of this facet of perceptual-motor skill and its acquisition. In particular, we suggest three steps to be considered in future work.

4.1 *Can a performance outcome be achieved via a variety of gaze patterns?* - An over-arching consideration for future work is whether the same level of success can be achieved after exploiting different patterns of gaze. There are likely to be both commonalities and differences in gaze patterns of performers at respective skill-levels and so research is needed to understand the nature of these variations. Literature on this issue is sparse; although some evidence suggests that individual differences in gaze behaviour exist between performers of the same skill level when successfully completing the same task [24, 25]. For example, Croft et al. [49] reported inter-individual differences in the gaze behaviours utilised by skilled youth cricket batsmen when successfully executing cricket strokes. While some participants demonstrated a pursuit tracking behaviour where the ball was fixated during its trajectory prior to bouncing, other batsmen rarely foveated the ball [50]. Moreover, research that has presented individual-participant variations in QE data during golf putting [51] and ten-pin bowling [52] indicates that putative optimal QE durations were not necessary for successful performance for a given task. In line with research on coordination summarised above, such findings implicate degeneracy in perceptual-motor control as different individuals' utilise different gaze patterns in order to achieve performance outcomes [53].

The highlighted findings point to the idea that variability in gaze behaviour is correlated to variability in movement coordination. Indeed, given that gaze patterns are the product of movements of the eyes; this association should not be unexpected. As has been argued for the control of coordination [33], the bandwidth (solution manifold) of variability in gaze would increase or decrease depending on the number of gaze patterns that can be used to achieve outcomes in a given task [53, 54]. Investigations of basketball jump-shot and free-throw performances have revealed that the bandwidth of final fixation durations that underpin successful performance change relative to these different shooting styles [54, 55]. During the execution of jump-shots, only a small bandwidth of gaze patterns appear to support successful performance [56], whereas a number of gaze patterns appear possible prior to successful free-throw performance [54, 55]. In line with the observation of a large bandwidth of gaze patterns during free-throw execution, inter-individual analysis of the shooting actions of different skilled basketball players by Button and colleagues [57] revealed that coordination of elbow and wrist actions differed from throw to throw, allowing each player to adapt to subtle differences in ball release parameters and maintain desired performance outcomes [58]. Together, these results point to the existence of a bandwidth of gaze-coordination variability - standard deviation of joint variables and gaze durations - which allows a combination of joints (e.g., elbow and wrist) to act in synergy to achieve successful performance outcomes during skilled action [59].

4.2 *Are gaze patterns constrained by variability in an opponent's action?* – It is currently unknown whether a bandwidth of gaze behaviour may be required during anticipation tasks in order to adapt to the variable information revealed within another person's movement. Consider, for example, a goalkeeper anticipating the kicking actions of an opponent. In one instance, a kinematic location (e.g., orientation of the non-kicking foot) will support accurate anticipation, and in a second scenario, the *same* location will not facilitate accurate performance due to variability in kicking actions [60]. The implication is that for one trial, one pattern of gaze may underpin success, and then for the next trial, the *exact* same information source or gaze pattern will not offer success due to variability in the opponent's action. Moreover, research shows that kinematic information that emerges in the earlier moments of a kicking action is incongruent with final kick location [12]. Indeed, evidence indicates that the bandwidth of possible gaze locations may be much larger during the early phases of an opponent's action, while in order to exploit the later, more reliable information, a smaller bandwidth of gaze patterns may be needed [61]. Further to such evidence, there is a real need to examine variability in gaze patterns over time during the anticipation of the actions of other persons. Indeed, research has begun to show how a more comprehensive understanding of gaze behaviour time-series data can be developed through the use of contemporary data analysis approaches (e.g., Bayesian modelling) [62].

4.3 *Is one example of one expert's gaze pattern the best model for training gaze behaviour?* - Recent learning studies indicate that emphasising variability in practice conditions appears to be most effective in helping novices to improve the accuracy of perceptual-motor skill [63]. Although the currently deployed procedure of presenting one example of the gaze pattern of one expert during learning studies has provided promising evidence [5, 19], there would appear to be necessity to examine whether novices benefit from the observation of different gaze examples, including those of individuals of differing abilities. The move toward observation of a greater number of gaze examples is consistent with advances in observational learning research. Specifically, this literature has revealed that learning is enhanced when the demonstration comprises combinations of both expert and novice models [64]. This may explain the lack of success in aiming to train novices to replicate the gaze patterns of experts outside the literature on QE training [6, 21]. It follows that future research is required to examine whether there may be further benefits to gain from gaze training studies beyond current understanding if mixed-observation methods are adopted [65].

5. Conclusion

To summarise, in this article, we have aimed to provide a rationale for reconciling different approaches to expertise in the perceptual-motor skill literature. We have highlighted that movement coordination findings point to the beneficial role that variability can play in skilled performance. To date, gaze studies have yet to fully examine the role of variability in eye movements, meaning that the majority of approaches still seek to reveal and train purported universal optimal perceptual strategies. We should clarify that we have not suggested that putatively optimal gaze strategies, such as QE, have no potential value in enhancing skilled performance. Instead, we have argued that a more informed understanding of gaze patterns and learning will result from more attention on inter- and intra-individual variability of gaze behaviour. Based on the over-arching aim of developing current understanding on the role of variability in gaze, we have highlighted the need to better understand the relationship between gaze regulation and movement patterns during the control of one's own action, during the anticipation of another's actions, and during learning. There is real potential to make advances in understanding the role of inter- and intra-individual variability of gaze behaviours, which could be achieved by adopting a more individualised analysis approach rather than solely adopting conventional, group based averaging methods [66]. The outcome of such studies would hold important implications for the development of theory and applied practice in expertise research.

Compliance with ethical standards

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Conflicts of interest Matt Dicks, Chris Button, Keith Davids, Jia Yi Chow, and John van der Kamp declare that they have no conflicts of interest relevant to the content of this review.

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