Consciousness and Cognition 19 (2010) 63–76

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Implicit knowledge and motor skill: What people who know how to catch don't know

Nick Reed [a], Peter McLeod [a,*], Zoltan Dienes [b]

[a] Department of Experimental Psychology, Oxford University, Queen's College, Oxford OX1 4AW, UK
[b] Department of Psychology, University of Sussex, Brighton BN1 9QH, UK

ARTICLE INFO

Article history:
Received 25 March 2009
Available online 22 August 2009

Keywords:
Implicit knowledge
Ball catching
Unconscious control
Knowing how
Procedural knowledge
Subjective measures

ABSTRACT

People are unable to report how they decide whether to move backwards or forwards to catch a ball. When asked to imagine how their angle of elevation of gaze would change when they caught a ball, most people are unable to describe what happens although their interception strategy is based on controlling changes in this angle. Just after catching a ball, many people are unable to recognise a description of how their angle of gaze changed during the catch. Some people confidently choose incorrect descriptions that would guarantee failure of interception demonstrating unconscious knowledge co-existing with systematically different conscious beliefs. Where simple solutions to important evolutionary problems exist, unconscious perception needs to be impervious to conscious beliefs.

1. Introduction

If a dissociation can be demonstrated between the knowledge that controls someone's behaviour and their ability to report how that behaviour is controlled, the knowledge is said to be implicit. For example, if someone runs forward to catch a ball but cannot say how they knew that the ball was going to land in front of them, they have implicit knowledge of how to catch. The status of implicit knowledge is the subject of an unresolved debate (see, for example, Dienes, 2008; French & Cleeremans, 2002; Jiménez, 2003).[1] Some believe that implicit knowledge underlies a range of human information processing and have discussed the conditions under which it is acquired and its relation to explicit knowledge (i.e., knowledge which the possessor can report) (e.g. Cleeremans, 2008; Norman, Price, Duff, & Mentzoni, 2007; Runger & Frensch, 2008). But there are those who deny that the dissociation that would demonstrate implicit knowledge has been satisfactorily demonstrated (e.g., Perruchet & Gallego, 1997; Shanks, 2005). Perruchet and Gallego said: "… there is no place for implicit knowledge or implicit representations. The perceptual contents and the internal representations built from perceptual contents are conscious." (p. 140).

If one considers everyday motor skills this denial may seem surprising. For example, people can ride a bicycle without being able to describe how they do it. Despite the apparently straightforward nature of such an example, little of the debate about implicit knowledge has examined whether the knowledge which underlies motor skills can be described by the skilled performer. One exception is the work of Masters and his colleagues who showed that when skill in golf putting develops

* Corresponding author.
E-mail addresses: peter.mcleod@psy.ox.ac.uk (P. McLeod), dienes@sussex.ac.uk (Z. Dienes).

[1] Much of the literature refers to implicit *learning* rather than implicit *knowledge* because most laboratory studies of this topic have involved participants learning a new task – hence the issue is whether they were aware of what they were learning. Ball catching is a skill which participants learnt years before they came to our laboratory so the issue is whether they are now aware of the knowledge that controls their behavior rather than what happened when they acquired it.

1053-8100/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.concog.2009.07.006

while performing a secondary task, participants report few rules to account for their learning (reviewed in Masters & Maxwell, 2004). But finding a dissociation in the laboratory between a determinable piece of acquired knowledge and its report has been elusive. Shea, Wulf, Whitacre, and Park (2001) investigated the learning of a specific structure in a complex motor task in which participants balanced on a platform and moved it to track a constantly changing target. Errors reduced with training on a repeating 25-s segment of the pattern, though participants were apparently unaware that a particular segment of this length had been repeated. However, Perruchet, Chambaron, and Ferrel-Chapus (2003) showed that in the Shea et al. study there were structures participants could more plausibly have learnt than the repeating segment itself. We do not know if the participants in Shea et al. learnt these structures consciously or unconsciously.

There is evidence from other domains that people can acquire implicit knowledge, though such claims are also disputed (Shanks, 2005). Reber (1967) originally showed that people exposed to sequences of letters generated from an artificial grammar came to be able to distinguish grammatical from non-grammatical sequences despite being unable to report the rules of the grammar. Indeed, people can reliably distinguish sequences when they believe they are literally guessing or using intuition (Dienes & Scott, 2005), when they would rather wager low rather than high (Persaud, McLeod, & Cowey 2007), and when they would rather bet on a transparently random process rather than their own decision (Dienes & Seth, in press). Thus, arguably people can know the grammaticality of a string without being aware of knowing. But in all these cases, people are aware of the sort of information that is relevant: bigrams, letter repetitions and so on, which people are largely able to correctly identify, at least as a guess, if forced (Dulany, Carlson, & Dewey, 1984). Perceptual motor skill learning may allow for a more clear-cut dissociation between conscious and unconscious knowledge.

In this paper we investigate what people can report about the knowledge they use when they decide to remain stationary, or to move forwards or backwards to catch a ball thrown directly towards them. That is, how they know whether, if they did not move, the ball would hit them or fall in front of them or fall behind. This is a good skill for investigating implicit knowledge because the sensory information that underlies it is generally agreed[2] (Dienes & McLeod, 1993; McLeod & Dienes, 1993, 1996; McLeod, Reed, & Dienes, 2001, 2006; Michaels & Oudejans, 1992). Further, it has the characteristics suggested by Mathews (1997) as appropriate for investigating implicit knowledge: "[Implicit] learning is especially adapted for action (i.e. doing the right thing at the right time) ... thus [it] tends to be tied to environmental cues that guide behaviour ... we badly need experiments that examine the properties of implicitly acquired knowledge at higher levels of practice and skill development than typically found in the classical 1-h[our] experiment". The skill also has three of the characteristics which Berry (1994; cf also Norman et al., 2007) suggested were typical of implicit learning: (i) It is associated with incidental learning. Nobody tells children how to catch. They are told to keep their eye on the ball and then learn by watching objects thrown towards them and trying to catch them. (ii) It gives rise to a phenomenal sense of intuition. If you know how to catch and a ball is thrown towards you, you get an immediate feeling that you should run backwards or forwards to catch it. You do not do any conscious computation. (iii) It shows limited transfer. The knowledge used for intercepting or avoiding objects thrown towards you can be used for little else.

What happens when you watch an object thrown towards you? Fig. 1 shows α, the angle of elevation of gaze above the horizontal, as a stationary observer watches a ball approaching on a ballistic trajectory.[3] In the central panel the ball is going to hit the observer in the eye. For the early part of the flight where the ball is rising it is obvious that α will increase. But what happens when the ball starts to fall? Many people assume that because the ball is falling, and the eyes follow the ball, the angle of gaze will also fall. In fact, as can be intuited from the figure, for a flight which will hit the observer in the eye, at whatever part of the flight the line of gaze from observer to ball is drawn, the ball's next position will be above that line.[4] Therefore, the angle of gaze as the observer follows the ball will increase throughout the flight, reaching a maximum value just as the ball reaches the observer.[5] The rate of increase of the angle of gaze will diminish steadily throughout the flight as can also be intuited from the figure.

The upper and lower parts of Fig. 1 show what happens when the ball falls in front of the observer or goes over head. If the ball is going to land in front of the observer α will increase initially but a time will come when the ball falls below the previous line of sight from observer to ball. From this point α will decrease continuously, reaching 0° as it passes eye level. The nearer to the observer that the ball lands, the later in the flight will α start to decrease. If the ball is going to pass above the eye the angle of gaze will rise continuously throughout the flight, accelerating as it passes over the observer. These three patterns are not dependent on the launch parameters or the wind-resistance experienced by the ball.

---

2 The experiments reported here only concern balls coming directly towards the person catching the ball and it is for this sub-set of catches for which there is 'general agreement'. Optic Acceleration Cancellation (OAC) theory (see McLeod, Reed & Dienes, 2008) is the only account of how such balls are caught. Linear Optic Trajectory (LOT) theory has been proposed as an alternative to OAC theory as a theory of how people decide to move to intercept a ball but this only applies when the fielder has to move sideways as well as backward or forward to catch the ball (see Shaffer et al. 2003).

3 An object will be on a ballistic trajectory if it was given an initial impulse upwards and forwards and then proceeds under the joint effects of downward gravitational acceleration and retardation produced by air-resistance. Fig. 1 does not show how the angle of gaze changes when someone watches an approaching object which has its own propulsion (such as a bird) or which generates significant lift from its forward motion (such as a Frisbee).

4 A ball on a ballistic trajectory is accelerating downwards and decelerating forwards. If its current vertical and horizontal velocity take it below the line representing the direction of gaze from observer to ball (and, therefore, α decreases) it can only fall further below as the flight progresses and thus will not hit the observer in the eye. Ergo, if the object hits the observer in the eye at the end of the flight, α will have increased throughout the flight.

5 Chapman (1968) provides an analytical proof that α increases continuously for someone watching an object in parabolic flight that would hit them in the eye. Dienes and McLeod (1993) extended Chapman's analysis to show that this was also true for an observer watching a ballistic flight when the effect of wind resistance on the trajectory was taken into account.

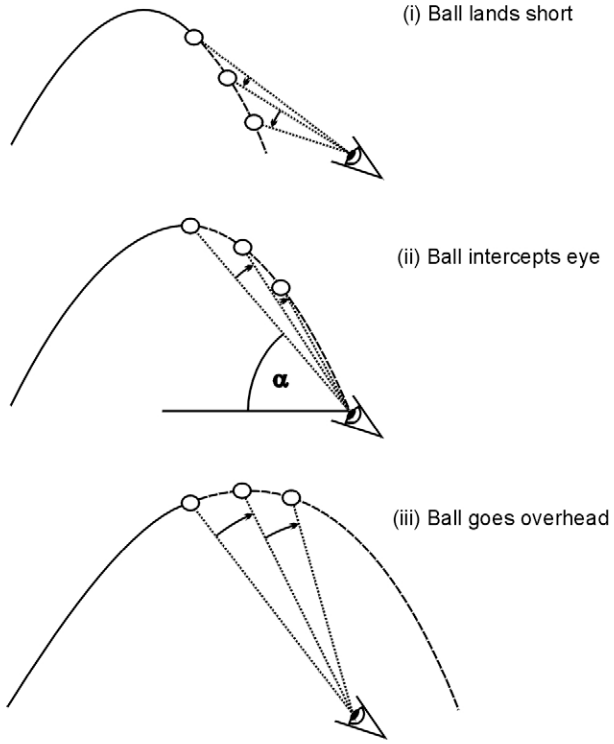

Fig. 1. How α changes with time for examples of the three possible classes of trajectory: Upper – a ball falling in front of the observer. Middle – a ball that will hit the observer in the eye. Lower – a ball that will go over the observer's head.

The pattern of continuous increase at a decreasing rate is only strictly true for objects hitting the observer in the eye. Balls hitting the observer just above or below the eye will show a sudden increase or decrease in α at the very end of the flight. However, balls coming close to the head produce a sudden looming cue as they approach, triggering a reflex eye closure. The result is that the final fraction of a second of the flight when the angle of gaze suddenly rises or falls is unlikely to be observed. Thus the angle of gaze to a ball that goes close to the eye will, like balls that hit the eye, appear to the observer to have risen continuously at a decreasing rate. The experiences observers get from watching balls thrown towards them, therefore, divide into three categories. When they watch a ball falling in front of them the angle of gaze rises and then falls. When they watch one going over head the angle of gaze increases throughout the flight, accelerating towards the end. But when they watch a ball that approaches on a trajectory which lands close to the eye, the angle of gaze increases throughout its flight at a decreasing rate. As soon as an infant can track moving objects (and this is very early in life, see von Hofsten, 1980) it will start accumulating these experiences. Every adult has experienced these three patterns innumerable times.

What use do people make of this information? Given that the pattern of increase at a decreasing rate is followed by something hitting the observer in the face one might expect classical conditioning processes to ensure that this pattern was memorable. It would not be surprising if people learnt to use it as a signal to move to avoid being hit by an approaching object. It also appears to form the basis of the strategy that people use when they want to catch a ball – that is, when they want to achieve rather than avoiding a collision with the ball. When people run to intercept a ball they choose a speed such that the angle of gaze rises continuously but at a decreasing rate (Dienes & McLeod, 1993; McLeod & Dienes, 1993, 1996; McLeod et al., 2001, 2006; Michaels & Oudejans, 1992).[6] If they are running forward and the angle of gaze starts to decline (indicating that the ball will fall in front) they accelerate; if the rate of increase starts to accelerate (showing that the ball will land behind) they decelerate. If they are running backwards, *vice versa* (Dienes & McLeod, 1993; McLeod & Dienes, 1996; McLeod et al., 2006).

Since the pioneering work of Chapman (1968), the assumption that controlling the rate of increase of the angle of gaze is people's interception strategy has been known as the Optic Acceleration Cancellation (OAC) theory of interception. It is a prospective theory of interception (see Berthental, 1996; Zago, McIntyre, Senot, & Lacquanit, 2009) as it is assumed that the fielder does not make a prediction about where to go from the ball's initial flight parameters. Rather, he operates a servo mechanism which continually adjusts his speed as he runs. The strategy ensures that the fielder arrives at the place where the ball will land at the same time as the ball (if he can run fast enough to keep the angle of gaze changing at an appropriate rate) but does not tell him where that point is in advance. Although empirical studies of catching where fielders' movements

[6] Some of these studies show that the tangent of α increases at a constant rate as people run. If tan α increases at a constant rate α will increase at a decreasing rate.

have been filmed show that fielders reach the point where the catch will be made at the same time as the ball (McBeath, Shaffer, & Kaiser, 1995; McLeod & Dienes, 1996; McLeod et al., 2006; Shaffer, McBeath, Roy, & Krauchunas, 2003) anecdotal reports from people watching games like baseball (e.g., Chodosh, Lifson, & Tabin, 1995) have claimed to observe fielders moving to the place where they will take the catch and waiting for it. A resolution of this contradiction was offered by McLeod et al. (2006) who showed that the OAC theory predicted that a fielder who was at the correct depth to catch the ball but laterally displaced from the interception point might move laterally to the correct point and then wait for the ball. It is only in depth that OAC theory predicts the fielder will arrive at the interception point at the same time as the ball.

An argument sometimes used to deny that a skill like riding a bicycle demonstrates implicit knowledge is to claim that the sensory information underlying the skill is not reportable and so falls outside the domain of knowledge to which the implicit/explicit distinction can be applied. This argument cannot be applied to the knowledge involved in the skill of ball catching as the sensory information which controls this skill, the change in the angle of elevation of gaze as the approaching ball is tracked, is inherently reportable. Anyone knows and can in principle report whether their gaze is going up or down.

We have explored the extent to which people can describe how they decide to move backwards or forwards with three different groups of subjects, varying the cues given to elicit report of the knowledge involved. First we asked people to tell us how they thought they made the decision without prompts or hints, to see what people know about the cues they use and how they use them. Since none of this group mentioned the sensory signal that we believe people do use to control their backward/forward movement (the changing angle of elevation of gaze) we described this signal explicitly to a second group and asked them imagine how it changed as they watched a ball being thrown towards them. Again, people were poor at describing how this cue varied when it involved watching a ball that they could catch. Shanks and St. John (1994) believe that a weakness of studies of implicit knowledge that ask people what they know is that the recall condition may not be sufficiently close to the actual performance of the skill to enable knowledge to be recalled. So we gave a third group a series of descriptions of how their angle of gaze might change, asked them to think about how their angle of gaze changed as they caught a ball and then asked them immediately afterwards which description most closely matched the experience they had just had.

2. Experiment 1

The first experiment was a direct attempt to see if people can describe how they decide whether to move backwards or forwards to catch a ball coming towards them by simply asking them what their strategy was. Although free report is seen by some as the most natural measure of whether knowledge is implicit or explicit (e.g., Rünger and Frensch, in press) others think it suffers from the problem of sensitivity. Participants may have a theory but are not very confident about it and do not want to express it. We believe it is useful to see what people say without any of the experimenters' preconceptions about what sort of information they might hold influencing the questions they are asked to elicit recall.

2.1. Method

2.1.1. Participants

These were 14 males and 4 females, aged 19–27, all of whom considered themselves of above average skill at ball games.

2.1.2. Task

The participants were asked to imagine catching a ball thrown towards them from 20 m away. They were asked to imagine a ball which they could catch without moving, one which they knew was going to land in front of them and they would have to move forward to make the catch, and one which they knew was going over their head and they would have to move back to catch. They were asked how they would know that they were in the right place or that they would have to move. If they had to move they were asked how they would know that they were moving fast enough to catch the ball.

2.2. Results

Only one participant mentioned the sensory signal which underlies this judgement – the changing angle of gaze as they watched the approaching ball.[7] The remainder fell into two groups. One group attributed their behaviour to "experience". This is undoubtedly correct but none of the participants were able to describe what they had learnt from "experience". The other group said that they used the apex of the flight of the ball to decide what to do. Typically their response was that if the apex fell half way between them and the launch point they thought they were in the right place to catch the ball, if closer to the launch point they ran forward, and if nearer to them they ran back. This theory is wrong on all counts! First, fielders start to run in the correct direction before the ball reaches the apex of its flight (McLeod & Dienes, 1996). Second, if the ball comes towards the fielder the angle of gaze increases smoothly as the ball passes through the apex. There is nothing to tell the fielder when the ball is at its apex. Third, as Brancazio (1985) showed, because of the effect of wind resistance, balls with velocities

[7] This was a physics graduate student who tried to work out the answer from first principles. He realised the importance of angle of gaze (although his theory of how it was used was incorrect) but said he had not thought of this before the experiment.

typically met in ball games do not follow symmetrical trajectories. Even if the apex of the trajectory were visible it would not be an accurate predictor of where the ball would fall.

2.3. Conclusions

Experiment 1 confirms what some might have intuited from their own experience. People are not able to correctly describe on what they base their decisions to move backwards or forwards when they catch a ball coming towards them. Curiously, those who did offer an account gave one which would appear to be based on imagining a ball flight seen from the side when the apex of the flight *is* a salient point. It is unrelated to the experiences the participants have had watching balls coming towards them and moving backward or forward to catch them.

When asked why the correct use of the grammar of their native language by people who could not describe the rules of grammar was not a straightforward case of behaviour under the control of unconscious knowledge, Shanks and St. John (1994) responded that the rules of the grammar might be represented in a non-symbolic way. They might be represented by the weights of a neural network. Since connection weights are, presumably, not reportable they claimed that the use of the representation coupled to an inability to report it did not constitute an example of implicit knowledge. The mapping from changing angle of gaze to control of the fielder's acceleration which underlies catching is a natural candidate for representation with a neural network, so perhaps Shanks and St. John would make the same response to the demonstration in experiment 1. In the next two experiments we investigate what people can report about the sensory information which underlies the interception strategy they use to catch a ball coming towards them – the pattern of change in angle of elevation of gaze as they watch the ball. Change in angle of gaze is inherently reportable – people know whether their gaze is moving up or down.

3. Experiment 2

Having established in the first experiment that people do not report the sensory information they use to control their actions, we gave them that cue to see whether this would prompt more accurate report of the strategy used. In this experiment we again used free recall rather than recognition which is used in experiment 3 where participants are given a number of alternatives (including the correct one) to choose from. There are advantages and disadvantages of either method. Free recall may suffer from the problem of sensitivity. But it avoids the problem of participants being inadvertently led to infer the correct answer by giving the subjects too much information or to infer the wrong answer because they are misled by tempting alternatives.

3.1. Method

3.1.1. Participants

These were 24 university students, 19 male and 6 female, aged 17–32. Their familiarity with ball games ranged from those who did not play any ball game regularly to those who played at top amateur level.

3.1.2. Task

Angle of elevation of gaze was explained graphically to participants and examples given of the way it would change as they watched a moving object such as a rocket rising in the air or a parachutist descending to the ground. They were asked to imagine watching a ball thrown gently towards them by someone standing 8 m away and to describe how their angle of gaze would change as they watched the ball if it was thrown so that:

(1) it landed a couple of metres short of your position,
(2) you caught it low at around knee level,
(3) you caught it in front of your eye (it would hit you in the face if you missed it),
(4) you had to reach high above your head to catch it,
(5) it flew over your head.

They were also asked to give a confidence rating for their judgements on a scale from 0 (pure guess) to 10 (certain).

In the upper part of Fig. 2 trajectories of the sort described to the participants are shown (this figure was not shown to the participants). The trajectories were computed for balls given a launch angle of 45° and launch velocities that led to them reaching the required end point, with a value of drag appropriate for a tennis ball thrown at the launch velocity of the ball. The flights were generated by the method of approximation and numerical integration outlined in Brancazio (1985). In the lower part of the figure the angle of gaze of the stationary observer watching balls approach on these trajectories is shown. Although the precise way that α changes depends on the initial launch angle and velocity, the general pattern does not. Whatever the ball's trajectory, the angle of gaze to balls which will fall short or are caught low increases initially and then declines; to balls which will reach the observer at eye level it increases continuously throughout the flight at a decreasing rate; to balls caught high or going over head it increases, accelerating towards the end.

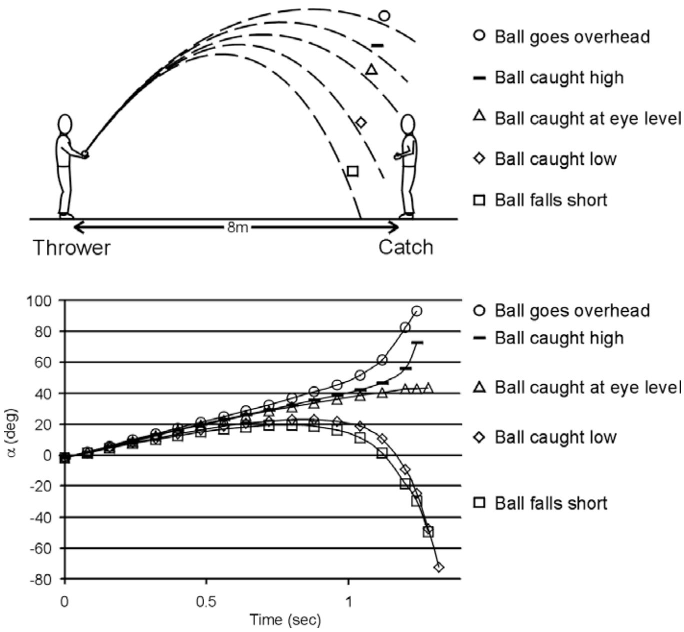

Fig. 2. Upper – trajectories of the sort participants were asked to visualise from the point of view of the person towards whom the ball was thrown. Lower – how the angle of gaze would change as a stationary observer watched balls on these trajectories.

3.2. Results

The descriptions of the way the angle of gaze would change throughout the flight were scored on a three point scale: 1 for a basically accurate description; 0.5 for a description in which some elements were correct but some wrong; 0 for one which was fundamentally incorrect. To check on the consistency of the scores the answers were marked by three independent judges. There was significant agreement between the three judges (Kendall's $W = 0.21$, $\chi^2(2) = 9.9$, $p < .01$).

The results are shown in Figs. 3 and 4. Fig. 3 shows the mean score for the descriptions of the way that angle of gaze changes for a catcher watching a ball falling short, one caught low, one caught at eye level, one caught high and one which was going over head. Fig. 4 shows the mean confidence level for each judgement. Two things are clear. First, the participants can accurately report how their angle of gaze would change for all trajectories except for a ball caught at eye level. Mann–Whitney tests confirm that reports for balls caught at eye level are less accurate than for balls on any of the other trajectories ($p < .001$ in each case). Second, there is no correlation between participants' confidence and their accuracy. Confidence is similar in all conditions although the accuracy varies from 98% to 28%. This is confirmed by a Friedman test that shows no difference in participants' confidence in their answers in the five conditions ($\chi^2(4) = 5.8$; $p > .2$).

3.2.1. Correlation with skill

The pattern of gaze change which most participants do not report accurately (watching a ball caught at eye level) is associated with many everyday occurrences other than catching balls. People often throw things towards someone which they

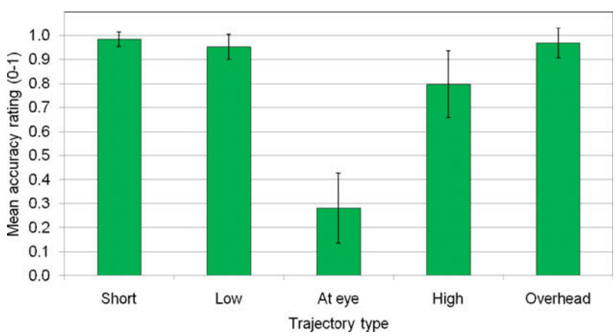

Fig. 3. Experiment 2. Mean accuracy scores for reports of how the angle of gaze would change for a catcher watching balls approach on the five trajectories shown in the upper part of Fig. 2.

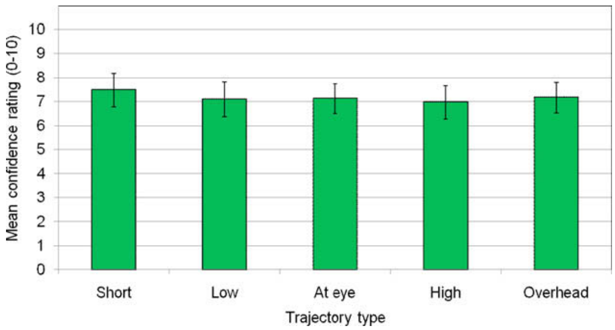

Fig. 4. Confidence ratings for the judgements shown in Fig. 3.

want them to catch. But it is possible that skilled ball game players would be better at making the judgement than non-players. To check whether the incorrect answers might be due to lack of experience, participants were rated on a three point scale, on the basis of self-report, as non-players, average, or skilled. Those who rarely or never participated in ball sports were assigned to the non-player category ($N = 3$). Those who played regularly but only on a social basis were classified as average ($N = 14$). Those who played ball sports at a representative level (for the University or at regional level) were classified as skilled ($N = 7$). The correlation between these ratings and the accuracy of the responses in the 'Caught in front of the eye' conditions was not significantly different from zero (Kendal's tau = −0.12, $p > .3$). This conclusion is confirmed by ANOVA with skill and trajectory type as factors and accuracy as the dependent variable. There was no main effect of skill ($F(2, 105) = 0.411$; $p = .663$) The inability to report accurately on how your angle of gaze changes as you imagine watching objects thrown towards you that you could catch at eye level is not a function of practice at ball games.

3.3. Conclusions

Most participants imagined that when they watch a ball coming towards them on a trajectory which would hit them in the face if they did not catch it, the angle of gaze would go up and then down. One third reported the entirely erroneous view that the angle of gaze would go up and then down in a symmetrical fashion around the apex of the flight. As the lower part of Fig. 2 shows there is no way for the observer of an approaching ball to know when the ball is at its apex. The angle of gaze continues to increase smoothly as the ball passes through the apex. The misconception that they use information about when the ball reaches its apex is presumably driven by the belief that as the ball goes up and then down, their gaze must do the same when they follow it. The information they have received from watching objects that have been thrown towards them and would hit them in the face if they had not caught them or avoided them is not represented in a way which is reportable. Or, at least, it is represented so weakly that an erroneous belief is reported instead.

Assuming that these participants are like all the others who have ever been reported (Dienes & McLeod, 1993; McLeod & Dienes, 1993, 1996; McLeod et al., 2001, 2006; Michaels & Oudejans, 1992) they use the knowledge that they cannot report to control their actions when they move to catch a ball thrown directly towards then. If people are unable to report the sensory information that they use to control interception we have a *prima facie* example of an action under the control of implicit knowledge. Further support for this claim comes from the fact that the participants were just as confident about the inaccurate reports as they were about the accurate reports. Participants appeared unaware of any discrepancy between their reports and their behaviour. The information that controls their behaviour is not available to reduce confidence in their inaccurate reports, satisfying the 'zero-correlation criterion' of unconscious knowledge (Dienes, 2008).

In a variant of this experiment we asked a new set of participants what would happen to their angle of gaze as they moved either forward or backward to catch balls (rather than remaining stationary) with the same set of five landing points. That is, balls falling in front of them as they moved forward or behind them as they moved back, or caught high or low, or caught at eye level. The results were the same. Whether imagining moving forward or back, participants could correctly describe what would happen to their angle of gaze in all conditions except the ball caught in front of the eye. Very few people said that in this condition the angle of gaze would go up continuously. Most thought it would go up and then down.

4. Experiment 3

In a pessimistic review of the experimental evidence for implicit learning Shanks and St. John (1994) concluded that no satisfactory demonstration of a dissociation between information controlling behaviour and participants' ability to report it had yet been shown. They suggested two criteria that an acceptable demonstration should satisfy. The Information Criterion is the requirement to show that the information that participants fail to report really is the information that is controlling their behaviour. The Sensitivity Criterion is the requirement for the experimenters to show that they have done all they could reasonably do to elicit the information from the participants.

In experiment 3 we explore two of the ways in which Shanks and St John recommend that experimenters could address the issue of Sensitivity. (In our experiments the Information Criterion is met because the strategy that is used to move backwards or forwards to catch balls in the plane of the observer (move so that the angle of gaze increases at a decreasing rate) is known. There is further discussion of this point in the Correlated Hypotheses section of the Discussion.) The first is the idea that free recall may not be the most effective way of eliciting information from memory. People might have information but fail to report it because they lacked confidence in it. The argument is somewhat implausible in experiment 2 as participants reported a high degree of confidence in their responses. However, in experiment 3 we used recognition rather than free recall to see whether more accurate information could be elicited in the 'Caught in front of the face' condition. Participants were given a number of descriptions of the way that their angle of gaze might change as they tracked the approaching ball (including the correct one) and asked to choose the one they thought most accurate.

A second suggestion of Shanks and St John is that the conditions in which information is retrieved should be as close as possible to the conditions in which it is used during execution of the skill. Imagining what would happen when you watched a ball is not the same as watching one. Participants might be aware of the information while performing the task but unable to recall it out of context. To address this we asked participants to catch a ball, thinking about the way their angle of gaze changed as they did so, and then immediately afterwards select a description of the way it had changed as they took the catch. The ball position and eye position of the participants were filmed so that the actual change in angle of elevation of gaze experienced by the fielder could be compared with their report of their experience.

4.1. Method

The experiment was similar to the previous one in that participants were asked to report on the way that their angle of gaze changed as they imagined or watched balls falling in front of them, caught low, caught in front of the face, caught high, or going over head. There were two differences from the previous experiment. The first was that participants were given a set of options to choose from in describing how their angle of gaze changed (i.e., recognition rather than recall). The second was that participants responded first after imagining the flights (as in experiment 2) – the Pre-catch condition – and then following an attempt to catch a ball – the post-catch condition.

4.1.1. Participants

These were 5 males and 4 females university students, with ages ranging from 19 to 29 years, mean 23.7.

4.1.2. Pre-catch task

Participants were given the same instructions as in experiment 2, defining angle of elevation of gaze and describing how it would change as they watched rising and falling objects. They were asked to imagine how their angle of gaze would change if they were watching a ball thrown towards them from 8 m falling in front of them, caught low, caught in front of their face, caught high or going over their head out of reach. Participants were asked to pick the most appropriate description of how their angle of gaze changed from the following set:

(1) Continuously down.
(2) Up and then down.
(3) Up and then dramatically down at the last moment.
(4) Up and then remaining constant.
(5) Up at a decreasing rate.
(6) Up at a steady rate.
(7) Up at an increasing rate.

Participants gave a confidence rating from 0 to 10 to their judgements.

4.1.3. Post-catch task

Participants watched a series of 20 balls thrown by hand from a distance of 8 m. They were asked to concentrate on how their angle of gaze changed during each trial while the ball was in flight and encouraged to catch the balls (in front of their face if possible). The balls were thrown directly toward the participant who was allowed to move forward or backward up to 1 m from the start position to try and catch the ball. Allowing the participants to move made it more likely that some balls could be caught in front of their face; preventing more than 1 m of movement ensured that some balls could only be caught low or high, and that some fell short or went over head. Thus some throws fell into each of the categories in Fig. 2. The launch angle of the balls was approximately 45°, giving flight times of around a second. After each trial, participants were asked to choose the best description of how their angle of gaze had changed from the response options listed above.

4.1.4. Recording of α

A video camera recorded the trials at 25 frames a second from a side-on position in which the ball's flight and the catcher's head were within the field of view. The ball and participant's eye position were measured from the film so that the value of α from catcher to ball could be obtained at 40 ms intervals. The original estimates of α from the frame-by-frame analyses

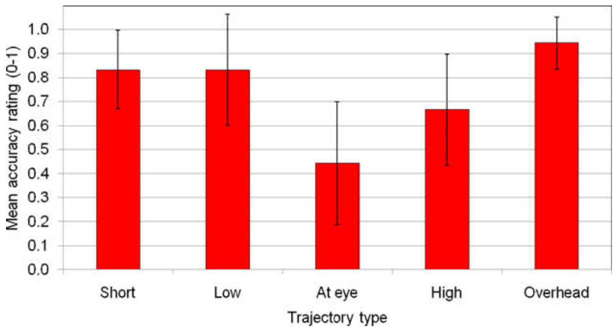

Fig. 5. Experiment 3. Mean accuracy scores for recognition judgements of how the angle of gaze would change for a catcher watching balls approach on the five trajectories shown in the upper part of Fig. 2.

were smoothed by replacing the value of α for each frame with half its original value for that frame plus a quarter of the value from each of its nearest neighbours.

4.2. Results

4.2.1. Pre-catch

The accuracy and confidence results are shown in Figs. 5 and 6. As in experiment 2, where participants reported in their own words how they imagined their angle of gaze would change, performance was worst in the 'Caught in front of the face' condition. Mann–Whitney comparisons showed that performance in this condition was significantly worse than all other conditions except 'Ball caught high' ($p < .04$ in each case). As in experiment 2, there were no differences in confidence across conditions despite the differences in accuracy (Friedman, $\chi^2(4) = 2.4$; $p > .6$). Performance in the 'Caught in front of the face' condition (0.44) was more accurate than in experiment 2 (0.28) but this difference failed to reach significance (Mann–Whitney, $z = -1.30$, $p = .194$). Assessing knowledge with recognition rather than recall produced a non-significant improvement in the ability of people to identify how their angle of gaze would change watching a ball that was caught in front of the face. More than half the participants still failed to choose the correct answer.

The participants were rated for ball games skill using the same criteria as in experiment 2. Four were rated as non-players, three as average and two as skilled. As in experiment 2 there was no relation between ball skill and the accuracy of the judgements (mean accuracy: non-players 0.775, average 0.700, skilled 0.750; $F(2, 42) = 0.194$, $p = .824$). But there was a significant effect of skill on the confidence that the participants had in their judgements (non-players 5.35, average 6.27, skilled 7.70; $F(2, 42) = 6.286$; $p = .004$). Among these participants increased experience and skill at ball games lead to judgements that were no more accurate but were made more confidently.

4.2.2. Post-catch

From the video it was possible to identify catches where each participant had caught the ball in front of the face. On these trials their selection from the alternative descriptions of how the angle of gaze changed was more accurate than in the Pre-catch condition – a mean of 0.53 compared to 0.44 in the Pre-catch condition but this difference failed to reach significance (Wilcoxon, $Z = -0.512$, $p = .61$).

Fig. 7 shows the values of α experienced by each participant on the trial in which the ball was caught closest to eye level. (The figure demonstrates that when people move to take a catch at eye level α does indeed increase throughout the catch at a decreasing rate.) The participants are grouped according to the accuracy of their recognition judgements. The top trace is for

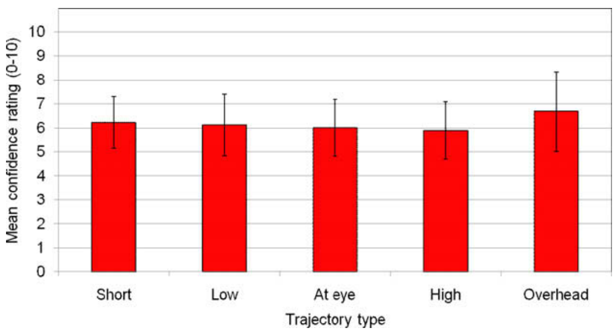

Fig. 6. Confidence ratings for the judgements shown in Fig. 5.

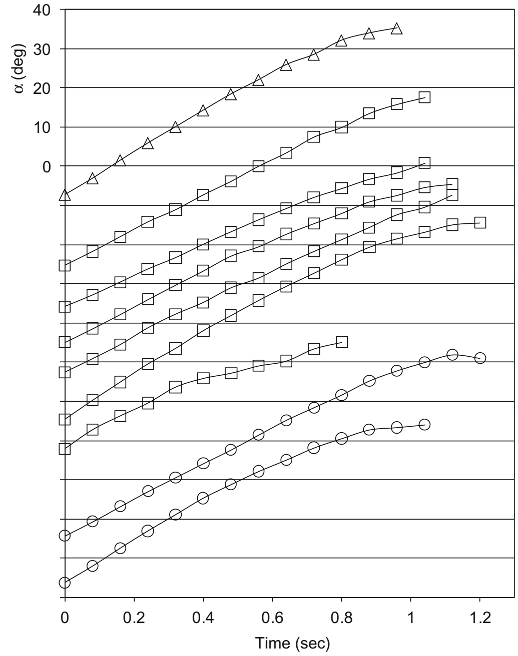

Fig. 7. The values α experienced by participants in experiment 3 when catching the ball at eye level until 40 ms before it was caught. The angle of gaze in degrees is given for the top participant. Other participants have been separated vertically to make their results easier to see. The participants are grouped according to the accuracy rating of their responses.

the only participant who chose the correct description. The next six all chose "up then constant". The bottom two chose "up then dramatically down at the last moment". The inability of all but one participant to recognise their experience is apparent. It might be argued that the rate of change of α was too low to be detected by the time the catch was taken so people were actually experiencing an angle which increased and then appeared to be constant. However, in an earlier experiment in which people caught balls (Dienes & McLeod, 1993) we showed people controlled the acceleration of α for angles of more than 50°; specifically people kept tan α increasing at a constant rate, implying that the OAC control strategy can be used at angles considerably greater than the maximum experienced in this experiment (around 35°). So it appears that the rate of changes of α experienced in this experiment can be detected.

4.3. Conclusions

The crucial condition is 'Caught in front of the face' at which the participants in experiment 2 were poor at imagining how their angle of gaze would change despite the fact that this is the condition which produces the visual experience that underlies their interception strategy when they catch a ball. Accuracy improved if they were given alternatives and allowed to select an answer rather than trying to generate it themselves but this improvement failed to reach significance. Accuracy improved further if the judgement was made immediately after catching a ball although again this improvement was not significant. However, taken together, post-catch recognition judgements in experiment 3 (mean accuracy 0.53) were better than free response judgements in experiment 2 (mean accuracy 0.28) (Mann–Whitney, $Z = -1.953$, $p = .051$). So it is possible to elicit more information about how the angle of gaze changes when watching a ball that is going to be caught in front of the face than is produced by free recall from memories of balls caught in the past. The emphasis Shanks and St. John put on the Sensitivity Criterion was vindicated to some extent.

However, performance was still far from perfect. This is surely surprising given the lengths to which we went to elicit the choice of 'up at a decreasing rate' in the Post-catch condition. Participants were asked to think about how their angle of gaze changed as they caught a ball in front of their face. They were then given a number of descriptions of how it might have changed and were asked to pick the one that matched their experience. One might have thought that participants could scarcely help but get the right answer independent of any knowledge they had of how to catch a ball. And yet, when, as Fig. 7 shows, their gaze had moved steadily upwards, most participants said that it went up and then remained constant and some actually claimed it went down. The 'sensitivity' argument is sometimes used against alleged demonstrations of implicit knowledge – the claim that people do have the information but are not very sure about it so they say nothing. This argument might be possible if people say nothing. But if they confidently report incorrectly then the 'sensitivity' argument becomes implausible.

5. Discussion

Despite the view that riding a bicycle is a straightforward demonstration of implicit knowledge because people cannot describe how they do it, perceptual-motor skills have not been widely used to investigate implicit knowledge. The assumption that motor skills are appropriate for studying implicit learning was the motivation for Broadbent's design of the dynamic control task (Broadbent, 1977) that produced a small literature (see Berry, 1997 for review). A few studies have investigated perceptual-motor implicit learning. For example, a study of how people draw circles (Vinter & Perruchet, 1999) showed that long lasting modifications to drawing behaviour can be induced while participants are unaware of the manipulation to which they have been exposed. Similarly, in terms of intuitive physics, Krist, Fieberg, and Wilkening (1993) showed that people throwing a ball could impart appropriately different velocities to it to ensure it had relevantly different trajectories, yet they were unable to report what the differences in velocities should be.

We go beyond these demonstrations by showing that the perceptual variable controlling action was correctly perceived only unconsciously. In terms of conscious perceptual judgments, people were not simply incomplete: They were often confidently wrong. In Experiment 1 people do not mention the way that the angle of elevation of gaze changes as they watch the ball despite the fact that this is the sensory information that controls how they move. Those who did report a strategy described one which cannot control the way they run because it relies on information which they do not get as they watch the ball. Experiment 2 showed that most people gave the correct answer when they imagined how the angle of gaze would change as they watched a ball which was going to land in front of them or go over their head but few could report what they would experience if they caught the ball at eye level although this is the information that underlies their interception strategy. Experiment 3 showed that many people were unable to recognise a description of how their angle of gaze had changed as they caught the ball at eye level even when they had just made a catch at eye level and had been told to think about their angle of gaze as they did so. The information that people do not report correctly controls their interception strategy. The inability to report or recognise the sensory information that controls their interception strategy is a demonstration that, for many people, interception is under the control of implicit knowledge. A remarkable observation in the final experiment was that some people chose a description of the change in their angle of gaze which was the opposite of the one they had just experienced – they claimed that their angle of gaze had been going down when in fact it had been going up. It seems that their (apparently logical) theory about what would happen (the balls falls so my angle of gaze must fall I follow it) is stronger than the experience that they had just had.

5.1. Correct report

It is possible that even when people correctly report what happens to angle of gaze in experiment 2 (when the ball is not caught and lands short or goes overhead) their responses are based on an erroneous theory about catching rather than on access to controlling knowledge. People's accurate reports may come from the coincidence that in these cases their (erroneous) theory happens to give the correct answer. Many people's views about their interception strategy reported in experiment 1 were based on the assumption that they could view the apex of the ball's flight. This idea presumably comes from imagining viewing a flight from the side (as if one were looking at the upper part of Fig. 2) when the apex *would* be a salient feature. In the conditions where participants provided correct answers the guess they would make by imagining a flight from the side would be correct if they believe that what the ball does, the angle of gaze will also do because it is following the ball. If the ball is going to fall in front the ball goes up and down and so does the angle of gaze. If the ball is going overhead it is clear that at the moment it passes overhead the angle of gaze is vertically upward so it is easy to imagine that the angle of gaze rises continually throughout the flight. It is only when the ball is caught at eye level that the ball does one thing (goes up and comes down) while the angle of gaze does another (goes up continuously). And this is the condition where most participants give the wrong answer. The conclusion that all the responses are based on a theory (derived from imaging flights from the side) rather than knowledge of how the angle of gaze changes based on experience of catching is supported by the confidence data. People were equally confident about all judgements, whether correct or incorrect. This suggests a common source for all judgements (cf Dienes, Altmann, Kwan, & Goode, 1995; Dienes & Berry, 1997; Dienes & Perner, 1999, 2004). The simplest theory is that people have no access to the controlling knowledge in any condition. (When the ball drops in front of them or goes over their head the angle of gaze provides the controlling knowledge because it provides the error signal people seek to null as they run.)

5.2. Correlated hypotheses

It might be argued that the variable controlling people's behaviour is not angle of gaze but one that just happens to be correlated with it. That is, the knowledge that controls behaviour might be explicit but we have not asked for it. We may have run into the ubiquitous problem of correlated hypotheses (Dulany, 1962) and failed to satisfy Shanks and St John's information criterion.

In claiming that people use the change in angle of gaze to control the speed at which they run backwards or forwards to catch a ball thrown directly towards them it is true that we are relying on a theory. But it is the only theory in the literature[8]

[8] The linear optic trajectory (LOT) theory of catching (McBeath et al, 1995; Shaffer et al., 2003) is a theory of how people combine sideways movement with backward and forward movement. For balls coming directly toward the observer it offers no control strategy other than that of optic acceleration cancellation.

and it gives a good fit to the data (99% of variance explained; Dienes & McLeod, 1993; McLeod et al., 2001, 2006). According to the theory, a servo mechanism alters a runner's speed so as to keep the angle of gaze increasing at a decreasing rate. Even if this is not correct, the strategy people use is one that keeps the angle of gaze increasing at a decreasing rate. Whatever variable people are controlling, it bears a monotonic relation to angle of gaze. The fact that people cannot translate that variable into a report of angle of gaze (when explicitly asked to do so in experiments 2 and 3) is an indication of its implicit or unconscious status given *global access* theories of consciousness (e.g. Baars, 1988; Del Cul, Baillet, & Dehaene, 2007; cf also Norman et al., 2007; Runger & Frensch, 2008). Conscious knowledge is *inferentially promiscuous* (Davies, 1989) on such accounts and can in principle be used in combination with any other piece of conscious knowledge for drawing inferences. If we are wrong and a variable other than angle of gaze is used for controlling behaviour this would bear such a direct relationship to angle of gaze that if it were consciously known the inferential link could be easily drawn when, as in our case, attention is drawn to the variable to which the link is to be made. (This is unlike many other situations in implicit learning where the problem of correlated hypotheses arise; Shanks & St. John, 1994.) Hence our claim that the knowledge must be unconscious, notwithstanding the problem of correlated hypotheses.

5.3. Network weights and knowledge

Cleeremans (1997) argued that the best account of implicit knowledge is not unconscious symbolic knowledge but the knowledge embedded in the weights of a connectionist network (cf also Pothos, 2007). A connectionist network is an appropriate way of modelling the knowledge that enables us to catch a ball. McLeod and Maass (2003) built a network with the changing angle of gaze to balls thrown towards it as input and acceleration backwards or forwards as output. The network used a genetic learning algorithm. That is, it started with minimal structure and a range of variants and those variants that got closest to balls thrown towards it were selected to form the basis of the next generation of networks. The next generation was produced by 'sexual' reproduction (i.e., random mixing of the structures of successful networks in the previous generation). After about 50 iterations of this selective process a structure evolved which was very successful at arriving at the place where balls would fall at the same time as the ball. The structure ensured that the network 'ran' at a speed such that its angle of gaze to the ball increased at a decreasing rate. That is, the network discovered exactly the same strategy as people.

We do not believe that people have an implicit symbolic representation "Run so as to keep the angle of gaze increasing at a decreasing rate". We assume that this information is encoded in the weights of a real neural network. The weights implement this rule so the rule has been represented but not symbolically (Dienes & Perner, 1999, 2003; Pothos, 2005). The rule is represented in a non-conceptual way; that is, the rule is not constituted of representations that can be freely recombined with any other representation. That is the nature of the weights of neural connections. The rule cannot be reported because verbal report requires the use of concepts. It may be that some people object to calling this 'knowledge' or a 'representation' but we see no reason to restrict the notion of knowledge to conceptual, symbolic representations (see Perner & Dienes, 2009).

5.4. Separation of control and awareness of goals

The proposal that we can be aware of the goals of our actions (to catch the ball) without being aware of the detail of how the visual-motor system achieves this (running at a speed which allows the angle of gaze to increase at a decreasing rate) is consistent with many observations in neuroscience. For example, it is argued on the basis of dissociations between patients that there is a separation between frontal and parietal systems in the control of action, frontal systems being involved in overall planning of actions and parietal systems involved in their moment to moment control (e.g., Andersen, Snyder, Bradley, & Xing, 1997; Posner & Petersen, 1990; Schwartz et al., 1995). Precise actions under visual control are possible in patients who have no reportable awareness of that visual information (Milner & Goodale, 1995). Automated actions such as making a pot of tea are performed without awareness of the detailed visual control of the individual actions (Land, Mennie & Rusted, 1999).

5.5. Why should knowledge be implicit?

A sceptic about the reality of implicit knowledge might ask why it would be beneficial for the cognitive system to be organised so that the conscious part of the system has no access to controlling information. Surely it would make constructive use of this information? Sun, Slusarz, and Terry (2005) suggest there can be synergistic relations between conscious and unconscious systems. Our experiments suggest another answer in the case of ball catching whereby the suggested flexibility of conscious knowledge (e.g. Cleeremans, 2005) can be such a disadvantage that we acquire an unconscious simple yet rigid solution. At a conscious level many people have an erroneous theory about how to intercept a ball that would be positively harmful were it used. They think that since the ball goes up and down, and the eyes follow the ball, the angle of gaze must go up and down. This line of argument may be persuasive to the conscious part of the cognitive system because the logic of the words seems impeccable. However, if someone holding this theory had control over the mechanism guiding their behaviour and ran so that their angle of gaze went up and down they would never catch the ball. In order to ensure interception the conscious part of the system would need to be prevented from interfering with the successful strategy discovered and implemented by the subconscious part of the system.

References

Andersen, R., Snyder, L., Bradley, D., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annual Review of Neuroscience, 20*, 303–330.

Baars, B. J. (1988). *A cognitive theory of consciousness*. New York: Cambridge University Press.

Berry, D. C. (1994). Implicit learning: Twenty-five years on. A tutorial. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 755–782). Cambridge, MA: MIT Press.

Berry, D. C. (1997). *How implicit is implicit learning?* Oxford: Oxford University Press.

Berthental, B. I. (1996). Origins and early development of perception, action, and representation. *Annual Review of Psychology, 47*, 431–459.

Brancazio, P. (1985). Looking into Chapman's homer: The physics of judging a fly ball. *American Journal of Physics, 53*, 849–855.

Broadbent, D. E. (1977). Levels, hierarchies, and the locus of control. *Quarterly Journal of Experimental Psychology, 29*, 181–201.

Chapman, S. (1968). Catching a baseball. *American Journal of Physics, 36*, 868–870.

Chodosh, L., Lifson, L., & Tabin, C. (1995). On catching fly balls (skilfully). *Science, 268*, 1681.

Cleeremans, A. (1997). Principles for implicit learning. In D. Berry (Ed.), *How implicit is implicit learning?* (pp 195–234). Oxford: Oxford University Press.

Cleeremans, A. (2005). Computational correlates of consciousness. In S. Laureys (Ed.), *Progress in brain research, 150*, 81–98.

Cleeremans, A. (2008). Consciousness: The radical plasticity thesis. In R. Banerjee & B. Chakrabarti (Eds.), Models of brain and mind: Physical, computational and psychological approaches, *progress in brain research, 168*, 19–33

Davies, M. (1989). Tacit knowledge and subdoxastic states. In A. George (Ed.), *Reflections on chomsky* (pp. 131–152). Oxford: Basil Blackwell.

Del Cul, A., Baillet, S., & Dehaene, S. (2007). Brain dynamics underlying the nonlinear threshold for access to consciousness. *PLoS Biology, 5*(10), e260. doi:10.1371/journal.pbio.0050260.

Dienes, Z. (2008) Subjective measures of unconscious knowledge. In R. Banerjee & B. Chakrabarti (Eds.), Models of brain and mind: Physical, computational and psychological approaches, *Progress in Brain Research, 168*, 49–64.

Dienes, Z., Altmann, G., Kwan, L., & Goode, A. (1995). Unconscious knowledge of artificial grammars is applied strategically. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 21*, 1322–1338.

Dienes, Z, & Seth, A. (in press). Gambling on the unconscious: A comparison of wagering and confidence ratings as measures of awareness in an artificial grammar task, submitted for publication.

Dienes, Z., & Berry, D. (1997). Implicit learning: Below the subjective threshold. *Psychonomic Bulletin and Review, 4*, 3–23.

Dienes, Z., & McLeod, P. (1993). How to catch a cricket ball. *Perception, 22*, 1427–1439.

Dienes, Z., & Perner, J. (1999). A theory of implicit and explicit knowledge. *Behavioral and Brain Sciences, 22*, 735–755.

Dienes, Z., & Perner, J. (2003). A theory of the implicit nature of implicit learning. In A. Cleeremans & R. French (Eds.), *Implicit learning* (pp. 214–232). Chichester: Psychology Press.

Dienes, Z., & Perner, J. (2004). Assumptions of a subjective measure of consciousness: Three mappings. In R. Gennaro (Ed.), *Higher order theories of consciousness* (pp. 173–199). Amsterdam: John Benjamins Publishers.

Dienes, Z., & Scott, R. (2005). Measuring unconscious knowledge: Distinguishing structural knowledge and judgment knowledge. *Psychological Research, 69*, 338–351.

Dulany, D. E. (1962). The place of hypotheses and intentions: An analysis of verbal control and verbal conditioning. In C. W. Eriksen (Ed.), *Behavior and awareness* (pp. 102–129). Durham, N. Carolina: Duke University Press.

Dulany, D. E., Carlson, R. A., & Dewey, G. I. (1984). A case of syntactical learning and judgment: How conscious and how abstract? *Journal of Experimental Psychology: General, 113*, 541–555.

French, R. M., & Cleeremans, A. (2002). *Implicit learning and consciousness: An empirical, philosophical and computational consensus in the making?* Hove, England: Psychology Press.

Jiménez, L. (Ed.). (2003). *Attention and implicit learning*. Amsterdam: John Benjamins.

Krist, H., Fieberg, E., & Wilkening, F. (1993). Intuitive physics in action and judgment: The development of knowledge about projectile motion. *Journal of Experimental Psychology: Learning, Memory and Cognition, 19*, 952–966.

Land, M. F., Mennie, N., & Rusted, J. (1999). The roles of vision and eye movements in the control of activities of daily living. *Perception, 28*, 1311–1328.

Masters, R. S. W., & Maxwell, J. P. (2004). Implicit motor learning, reinvestment and movement disruption: What you don't know won't hurt you? In A. M. Williams & N. J. Hodges (Eds.), *Skill acquisition in sport: research, theory and practice* (pp. 207–228). London: Routledge.

Mathews, R. C. (1997). Is research painting a biased picture of implicit learning? The dangers of methodological purity in scientific debate. *Psychonomic Bulletin and Review, 4*, 38–42.

McBeath, M. K., Shaffer, D. M., & Kaiser, M. K. (1995). How baseball fielders determine where to run to catch fly balls. *Science, 268*, 569–573.

McLeod, P., & Dienes, Z. (1993). Running to catch the ball. *Nature, 362*, 23.

McLeod, P., & Dienes, Z. (1996). Do fielders know where to go to catch the ball or only how to get there? *Journal of Experimental Psychology: Human Perception and Performance, 22*, 531–543.

McLeod, P., & Maass, B. (2003). Evolutionary connectionism. In P. Quinlan (Ed.), *Connectionism and developmental psychology* (pp. 345–365). Hove, England: Psychology Press.

McLeod, P., Reed, N., & Dienes, Z. (2001). Towards a unified fielder theory: What we do not yet know about how fielders run to catch the ball. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 1347–1355.

McLeod, P., Reed, N., & Dienes, Z. (2006). The generalised optic acceleration cancellation theory of catching. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 139–148.

Michaels, C. F., & Oudejans, R. D. (1992). The optics and actions of catching fly balls: Zeroing out optic acceleration. *Ecological Psychology, 4*, 199–222.

Milner, D., & Goodale, M. (1995). *The visual brain in action*. Oxford: Oxford University Press.

Norman, E., Price, M. C., Duff, S. C., & Mentzoni, R. A. (2007). Gradations of awareness in a modified sequence learning task. *Consciousness and Cognition, 16*, 809–837.

Perner, J., & Dienes, Z. (2009). Representation. In P. Wilken, T. Bayne, & A. Cleeremans (Eds.), *Oxford companion to consciousness* (pp. 567–571). Oxford: Oxford University Press.

Perruchet, P., Chambaron, S., & Ferrel-Chapus, C. (2003). Learning from implicit learning literature: Comment on Shea, Wulf, Whitacre, and Park (2001). *Quarterly Journal of Experimental Psychology, 56A*, 769–778.

Perruchet, P., & Gallego, J. (1997). A subjective unit formation account of implicit learning. In D. Berry (Ed.), *How implicit is implicit learning?* (pp 124–161). Oxford: Oxford University Press.

Persaud, N., McLeod, P., & Cowey, A. (2007). Post-decision wagering objectively measures awareness. *Nature Neuroscience, 10*, 257–261.

Posner, M., & Petersen, S. (1990). The attentional system of the human brain. *Annual Review of Neuroscience, 13*, 25–42.

Pothos, E. M. (2005). The rules versus similarity distinction. *Behavioral & Brain Sciences, 28*, 1–49.

Pothos, E. M. (2007). Theories of artificial grammar learning. *Psychological Bulletin, 133*, 227–244.

Reber, A. S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning and Verbal Behavior, 6*, 855–863.

Rünger, D., & Frensch, P. A. (in press). Defining consciousness in the context of implicit sequence learning: Theoretical considerations and empirical implications. *Psychological Research*.
Runger, D., & Frensch, P. A. (2008). How incidental sequence learning creates reportable knowledge: The role of unexpected events. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 34*, 1011–1026.
Schwartz, M., Montgomery, M., Fitzpatrick-DeSalme, E., Ochipa, C., Coslett, H., & Mayer, N. (1995). Analysis of a disorder of everyday action. *Cognitive Neuropsychology, 12*, 863–892.
Shaffer, D., McBeath, M., Roy, W., & Krauchunas, S. (2003). A linear optical trajectory informs the fielder where to run to the side to catch fly balls. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 1244–1250.
Shanks, D. R. (2005). Implicit learning. In K. Lamberts & R. Goldstone (Eds.), *Handbook of Cognition* (pp. 202–220). London: Sage.
Shanks, D. R., & St. John, M. F. (1994). Characteristics of dissociable human learning systems. *Behavioral and Brain Sciences, 17*, 367–447.
Shea, C. H., Wulf, G., Whitacre, C. A., & Park, J. H. (2001). Surfing the implicit wave. *Quarterly Journal of Experimental Psychology, 54*, 841–862.
Sun, R., Slusarz, P., & Terry, C. (2005). The interaction of the explicit and the implicit in skill learning: A dual-process approach. *Psychological Review, 112*, 159–192.
Vinter, A., & Perruchet, P. (1999). Isolating unconscious influences: The neutral parameter procedure. *Quarterly Journal of Experimental Psychology, 52A*, 857–876.
von Hofsten, C. (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Child Psychology, 30*, 369–382.
Zago, M., McIntyre, J., Senot, P., & Lacquanit, F. (2009). Visuo-motor coordination and internal models for object interception. *Experimental Brain Research, 192*, 571–604.