Perceptual-Motor Characteristics of Elite Performers in Aiming Sports

Bruce Abernethy

and

Robert Neal

Department of Human Movement Studies
The University of Queensland

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BACKGROUND TO THE PROJECT

There currently exists only a very limited amount of scientific literature on the nature of skilled performance in sports involving aiming skills. Relatively high profile sports such as rfile and pistol shooting have only very recently become the focus of scientific investigation whilst other aiming sports such as billiards and snooker, which also rely heavily on aiming skills, have received absolutely no attention from sports science. In all sports which involve aiming, clear differences in performance are apparent between the elite performers and the lesser skilled but it is far from clear what causes these differences in performance, be it innate or acquired perceptual–motor differences. No guidelines are currently available for the identification of potentially elite performers at a young age in aiming sports nor are there systematic guidelines in place across aiming sports as to what factors may be critical for the improvement of the average competitor to the elite level. The purpose of this project was therefore to determine what particular factors (or perceptual–motor characteristics) are important for skilled aiming performance and to isolate on what characteristics the elite performers differ systematically from their lesser skilled counterparts. To examine this question we studied the perceptual–motor characteristics of samples of expert and novice performers in two sports -- the static aiming sport of billiards and snooker and the dynamic aiming sport of clay target shooting.

The report that follows consists of a compilation of six separate papers that may be read collectively or in isolation from each other. The first three papers report on our testing within the sport of billiards and snooker. Papers 1 (pp. 1–59) and 2 (pp. 60–88) are scientific/technical papers addressing respectively the visual/perceptual and motor control characteristics of the expert and lesser skilled performers. Paper 3 (pp. 89–106) is a lay–level report directed specifically at billiards and snooker coaches and players. Papers 4 to 6 report on the testing of the clay target shooters and are similarly organised to the billiards and snooker reports. Paper 4 (pp. 107–141) reports in scientific language on the visual correlates of expert shooting performance, paper 5 (pp. 142–164) reports again in scientific language on the motor control characteristics of expert shooters, and paper 6 (pp. 165–180) summarises the clay target test results in lay language for coaches and shooters. Acknowledgement is made with each individual paper to the Australian Sports Commission for its support of this research and to the various individuals and groups who made the completion of this ambitious project possible.

VISUAL-PERCEPTUAL AND COGNITIVE DIFFERENCES BETWEEN EXPERTS AND NOVICES IN A SELF-PACED STATIC AIMING SKILL.

Bruce Abernethy, Robert J. Neal and Paul V. Koning

Department of Human Movement Studies

The University of Queensland, AUSTRALIA

Running Head: EXPERTISE IN AIMING

Abstract

The performance of seven expert, seven intermediate and 15 novice billiards and snooker players was compared on a range of general visual tests and sport-specific perceptual and cognitive tests in an attempt to determine the locus of the expert advantage in self-paced, static aiming sports. No significant expert-novice differences were apparent on standard optometric tests of acuity, ocular muscle balance, colour vision and depth perception nor on the relative frequency of unilateral and cross-lateral eye-hand dominances. Experts, however, were found to be superior in their ability to both recall and recognize rapidly presented slides depicting normal game situations but were no better than novices in recalling information from slides in which the balls were arranged randomly on the table. The expert group's superiority on the perceptual recall and recognition tasks was consistent with a deeper level of encoding for structured (meaningful) material. Experts were also shown, through the use of thinking-aloud and evaluation paradigms, to use a greater depth of forward planning in choosing appropriate shot options and to evaluate existing situations with greater accuracy, discriminability and prospective planning than do novices. The cognitive advantage is shown to be a potential contributor but not a total explanation of the superior performance of the experts on the perceptual tasks. Overall the results of this study are consistent with existing works on expertise in board games (e.g., Chase & Simon, 1973a, 1973b) and 'open' skill sports (e.g., Starkes & Deakin, 1984) in indicating that the expert's advantage is not a general but a specific one, arising not from physical capacities but from acquired processing strategies. It is concluded that training regimes that provide an opportunity for the acquisition of situation-specific knowledge and processing strategies are more likely to enhance the rate of skill learning than regimes which are directed at general visual capabilities.

The Nature of Expertise in a Self-Paced, Static Aiming Skill:

1. Perceptual and Cognitive Factors.

The past decade has seen a growing interest in the study of expert–novice differences in sport tasks as a window for understanding the acquisition of skill. Knowing what essential attributes distinguish the expert from the lesser skilled performer in natural activities provides the sport scientist and practitioner alike with a principled basis for determining what types of practice are most likely to be beneficial for enhancing the development of expertise.

To date, the majority of studies of expertise have implicitly adopted an information–processing model of human performance, measuring elements of performance which are either perceptual, cognitive, or motor in nature, under the assumption that skilled performance is directly dependent on the accuracy and efficiency of these component processing stages. The tests of perception, cognition, or motor control which have been used have varied substantially in the extent to which the stimuli presented and/or the response(s) required are general or sport–specific in nature. Reviews of the existing perceptual and cognitive studies on expertise in sport (e.g., Abernethy, 1987a; Rothstein, 1977; Starkes & Deakin, 1984) suggest that the more sport–specific the stimuli and response(s) used in the test task, and hence the more closely the processing demands of the test mimic those of the intact skill, the more probable it is that systematic expert–novice differences will be demonstrated. Generalized tests appear to remove much of the expert advantage, suggesting that experts and novices are not distinguished so much by the physical characteristics and capabilities of their sensory and central nervous systems as by the specific processing strategies they have developed to efficiently organize, interpret, and utilize the information their sport provides to them. For example, classic studies of experts in chess (de Groot, 1965, 1966; Chase & Simon, 1973a, 1973b), since replicated in studies of team sport experts (e.g., Allard, Graham, & Paarsalu, 1980), clearly demonstrate that the superior ability of experts to memorize the positions of pieces on the board (in the case of chess) or players on the court (in the case of basketball) is not due to their having greater memory capacities, as their advantage disappears if random patterns are used, but due to their more efficient encoding strategies for familiar material. In keeping with the tenets of an information processing or computational model of human performance, expert's superiority appears to be in terms of acquired information processing strategies (or 'software') rather than the physical capabilities of their perceptual and nervous systems ('hardware')(Abernethy, 1987; Starkes & Deakin, 1984).

The existing knowledge base on expertise in sport is not without its limitations however. For example, the majority of existing studies on expert–novice differences in sport perception and cognition have been largely 'piece–meal' in nature comparing sport groups of different skill levels on single parameters, pre–supposed to be of importance in that particular sport. In cases where more than one parameter has been measured on a particular group of subjects the tests are, more often than not, of similar kind (e.g., all general, non–sport–specific tests as in the case of much of the sports vision research). These limitations create at least two problems. First, these types of studies fail to recognize the undoubted multi–dimensional nature of expert performance (e.g., see Landers, Boutcher, & Wang, 1986) and the potential for poor capabilities on any particular parameter to be compensated by exceptional capability on one or more other vital components of the skill under examination (cf. Clarke, 1971). Second, there is a danger in drawing global implications about the nature of skill by collating trends across studies in which different sports are examined, different test protocols are used, and different criteria are used to categorize experts and novices (Thomas & Thomas, in press). Those few studies which have measured an array of both 'hardware' and 'software' parameters on the same set of experts and novices (e.g., Starkes, 1987) have typically examined 'open' sports i.e., sports which are dynamic in nature and characterized by an emphasis upon time-constrained decision-making and the perception of motion. Although comprehensive studies of expert rifle and pistol shooters (e.g., Daniels & Landers, 1981; Hatfield, Landers, & Ray, 1984, 1987; Landers, Christina, Hatfield, Daniels, & Doyle, 1980), archers (e.g., Landers et al., 1986; Salazar, Landers, Petruzzello, Crews, Kubitz, & Han, in press) and putting by golfers (e.g., Boutcher & Zinsser, 1990) have been undertaken, these studies on sports tasks performed under essentially stationary and non-time-constrained circumstances have focussed largely on psychophysiological correlates of expert performance. Although measurement of some standard optometric parameters have been included in these studies, few tests of sport-specific perception and cognition have as yet been undertaken in these activities.

The purpose of the current study was to attempt to determine the nature of the expert advantage in the self-paced natural aiming task provided by the sport of billiards and snooker and, in so doing, to determine if the 'hardware-software' view of expertise (Starkes & Deakin, 1984) remains viable beyond the domain of dynamic, 'open' skills. Expert performance in billiards and snooker would appear to require a unique combination of visual aiming skills (in visually aligning the cue with the required direct and indirect contact points on the cue and object ball respectively), unidirectional force control skills (in executing a precise force along a given line of action through the cue to the cue ball), decision-making skills (in selecting the correct shot option from the range available), and pattern recognition skills (in knowing where to best return the cue ball after a shot to achieve the most advantageous position for the next shot). It is the unique nature of this particular sport which makes it very difficult to draw assumptions regarding skill differences from studies of expertise conducted on other sports tasks. The essentially static nature of the aiming task means that the majority of visual perceptual studies directed at 'open' sports are of limited relevance whereas the emphasis the sport places upon fine but complex motor control limits the applicability of the existing cognitive studies of board games such as chess.

In an attempt to generate an accurate profile of expertise in the sport of billiards and snooker a series of both general and sport-specific visual-perceptual, cognitive and motor control measures were derived from groups of expert, intermediate, and novice players. In this paper we describe and discuss in turn the discriminatory power of the general optometric tests of vision, of the sport-specific perceptual tasks and of the sport-specific cognitive tasks.[1] A companion paper (Neal, Abernethy, & Engstrom, 1991) describes motor control and motor performance differences between the three groups.

SECTION 1: GENERAL VISUAL MEASURES

As vision is the dominant modality for human motor performance (Posner, Nissen, & Klein, 1976), it is perhaps not surprising to note quantum growth in the field of sports optometry in the past decade (e.g., Parker, 1980; Reichow & Stern, 1986a, 1986b). The increased involvement of optometrists in sport has resulted in an increase in routine measurement of standard optometric parameters such as acuity, stereopsis, and phoria on athletic populations and the advent of generalized visual training programs (e.g., Carlson, 1985; Revien, 1987; Revien & Gabor, 1981; Siederman & Schneider, 1983) aimed at enhancing sports performance through improvements in basic visual functioning. The rationale for such programs is grounded in the assumption that <u>superior</u> basic visual skills are an integral part of expert performance in sport, yet the evidence to indicate that this is in fact the case is far from convincing (Abernethy, 1986, 1987; see also Stine, Arterburn, & Stern, 1982). Although uncorrected visual defects may undoubtedly impair sports performance, and such defects may be surprisingly common even amongst groups of professional athletes (e.g., Garner, 1977; Sherman, 1980), there appears little empirical evidence that experts either self-select or acquire through the practice of their sport basic visual skills which are beyond that of the population norm. Although some early evidence was presented for experts being characterized by superior depth perception (e.g., Banister & Blackburn, 1931), ocular muscle balance (e.g., Graybiel, Jokl, & Trapp, 1955), and static peripheral range (e.g., Williams & Thirer, 1975), the bulk of more recent studies have failed to reveal consistent and systematic expert-novice differences on these parameters (see Abernethy, 1987, Garland & Barry, 1990, and Starkes & Deakin, 1984 for reviews). The majority of the available studies, however, have involved performers from dynamic sports and it remains possible that the failure to demonstrate systematic expert-novice differences using standard optometric test parameters is that these parameters are primarily static (i.e., there is no relative observer-object motion). If this is indeed the case, one might expect the standard optometric tests to be more capable of revealing expert-novice differences in the sport of billiards and snooker, where the visual demands of the natural task are also static.

The principal visual demand in billiards and snooker is with judging angles and distances and achieving accurate 'straight-line' sighting and aiming of the cue and the target spot on the cue ball. A number of standard visual measures might therefore be pre-supposed to be important in this sport.

(i) Acuity at both near and far distances may be important as a clear focus on points on the cue, the cue ball, and the target ball may be necessary to achieve accurate 'straight-line' sighting. The cue ball will typically be located at arm's length from the eyes (requiring acuity at approximately a 1 m distance) while the target ball might be from 1 to 4.5 m away. Lack of clarity in viewing either of these balls or the tip of the cue may result in poor performance.

(ii) Depth perception (the ability to perceive relative changes in object distance or depth) and stereopsis (the ability to discriminate differences in depth through the use of binocular vision) may well set important limits on a player's ability to judge the distance and, in turn, the angle of shots on the table.

(iii) Phoria measures, in both the horizontal and vertical plane, indicate the extent to which the extraocular muscles are balanced and hence the extent to which the axes of both eyes are in symmetry in viewing either near or far objects. Orthophoria (the case of perfect ocular muscle balance) or low levels of heterophoria (i.e., minimal deviations from perfect ocular muscle balance) may be advantageous, especially in the horizontal plane, in completing the accurate visual alignment requirements of billiards and snooker.

(iv) Minimal fixational disparity between both eyes during fused binocular viewing of the cue or target ball during the aiming process might also be expected to be important for expert performance in billiards and snooker, in avoiding cue alignment errors.

(v) If visual sighting capability is indeed an important factor in billiards and snooker performance then ocular dominance measures might also be expected to bear some relationship to skill level. Unilateral rather than cross-lateral eye-hand dominance configurations may be expected to be more prevalent in experts, this configuration allowing a closer alignment of the dominant eye to the controlling hand and cue.

(vi) Given the importance assigned to the different coloured balls in billiards and snooker, adequate levels of colour vision are also undoubtedly crucial for skilled performance in this activity.

The first part of this study set out to determine if expert players display levels of performance on these basic visual tests which are beyond population norms and beyond those of intermediate and novice players.

Method

Subjects

Seven expert billiards and snooker players, ranked within the top 30 within Australia, seven intermediate level club players, and a control group of 15 novice players, randomly selected from a University undergraduate student pool, participated in the study. The expert and intermediate players were recruited through the National Billiards and

Snooker Council. The expert group had, on average, 16.7 years of playing experience, (range=8–30 years), the intermediate group 19.8 years (range=1.5–45 years) and the novice group less than 1 year of experience. The greater years of playing experience in the intermediate than the expert group was a function of age differences between the subjects within the two groups; intermediates ranging in age from 12 to 61 years (M=36.9; Mdn=42) and experts from 20 to 45 years (M=33.3; Mdn=35). The novice group was a more heterogeneous one ranging in age from 18 to 29 years (M=21.6; Mdn=21). All subjects were male, participated voluntarily, and were naive to the specific purpose of each test within the study.

Procedures

Testing proceeded in two stages. Stage 1 involved clinical examination of the expert and intermediate subjects for uncorrected visual defects. This examination and testing was performed by two qualified optometrists from the Department of Optometry at Queensland University of Technology. Stage 2 involved comprehensive testing of both the expert and intermediate subjects and the novice subjects on a range of standard optometric tests. The purpose of this stage of testing was to determine if there were any systematic expert–novice differences in general visual performance which may be of use in explaining expert performance in billiards and snooker. This, and all subsequent testing described in this paper, was conducted in the Human Performance Laboratories of the Department of Human Movement Studies, University of Queensland. Subjects who normally wear corrective lenses while playing billiards and snooker were required to also do so throughout all phases of testing.

1. Clinical Screening Tests -- The following standard optometric measures were derived from the expert and intermediate subjects in the first phase of this study:

(i) Vernier acuity under both monocular and binocular viewing for static targets at optically far (6 m) and near (35 cm) distances;

(ii) Phoria or ocular muscle balance both horizontally and vertically for both near and far viewing distances. (In the phoria tests one eye was covered and the relative vergence changes in the absence of binocular fusion were recorded);

(iii) Ocular alignment during binocular fusion (assessed using a Mallett test at 6 m and 1 m distances);

(iv) Stereopsis, assessed using standard random dot stereograms; and

(v) Colour vision, assessed via the Ishihara method.

2. Comparative Optometric Tests In the second phase of this study all 29 subjects (novices as well as expert and intermediate players) were tested for comparative rather than screening purposes. Using a Bausch and Lomb Professional Vision Tester (Lafayette Instruments Co., Lafayette, IN; Cat. No. 71–22–41) subjects were measured on

(i) static acuity, monocularly and binocularly, at far (20'; 6.1m) and near (14"; 35cm) distances;

(ii) phoria, horizontally and vertically, at far and near distances; and

(iii) colour vision (tested at the far viewing distance).

In addition, depth perception was assessed using the Howard–Dolman apparatus over a test distance of 3.66 m (12 ') (the length of a full–size billiards table) and ocular dominance was assessed using a simple sighting test. Ocular dominance was expressed with respect to hand dominance and the relative frequency of unilateral and cross–lateral dominances was compared between the three skill groups using non–parametric procedures.

Results

Clinical Screening Tests

All of the subjects displayed both binocular and monocular vernier acuities at both the near and far test distances which were within the normal range and without the need for correction of any type.

One of the expert subjects displayed phoria measures in the horizontal plane at the near distance and in the vertical plane at the far distance which were outside the expected normal range and warranting correction. The phoria measures provide an indication of ocular muscle balance. In the horizontal plane esophoria refers to the state where the eyes have a tendency to 'toe inwards' excessively in fixating upon a given object or distance whereas exophoria is the term used to describe the tendency for the eyes to 'toe outwards' excessively during fixation. The one subject's horizontal phoria of 12.0 dipters exophoria fell well outside the range of 5 diopters (of either esophoria or exophoria) considered as the normal clinical range. A score of 3.0 diopters of right hyperphoria was also recorded for the same subject in the vertical plane at the far test distance. In a right hyperphoria the right eye is aligned higher than the left eye while viewing a stationary object. Phorias of greater than 1 diopter are not expected in the vertical plane, as such phorias generally give rise to diplopia (the perception of two images of a single object). Four of the subjects at the far distance and seven subjects at the near distance displayed orthoporia (i.e., no measureable ocular muscle imbalance) in the horizontal plane. In the vertical plane eight orthoporias were recorded on the far test and 12 on the near test.

Whereas the phoria measures in this instance were derived monocularly the Mallett test provided an indication of the alignment of the eyes during binocular fusion. Of the Mallett binocular fusion tests administered to this group of subjects, only one abnormality was detected – the same subject who displayed clinically significant levels of phoria also displayed a 1 diopter exophoric alignment at the closer (1m) target distance. One can imagine, however, that such an exophoria during binocular viewing at that distance may create significant difficulties in the sport setting in gaining precise alignment of the cue to the target spot on the cue ball.

Two of the subjects demonstrated levels of stereopsis poorer than expected from clinical norms while, perhaps not surprisingly, no colour vision defects were evident in any of the billiards and snooker players tested.

Comparative Optometric Tests

The mean acuity, phoria, and depth perception measures for the expert, intermediate, and novice groups in the second phase of the study are displayed in Table 1, along with one-way analysis of variance statistics comparing the groups on each of the measures.

Statistically significant group differences were evident on only one of the acuity measures. At the near test distance the binocular acuity of the intermediate skill group, while still remaining within clinical norms, was significantly poorer than that of both the expert and novice group. Although none of the other acuity measures differed significantly between groups the same general trend was also apparent in these measures i.e., the mean acuity scores for the intermediate group were poorer, on average, than those of the expert and novice group, whose scores, in turn, were very similar. This effect may be simply explicable in terms of the older mean age of the intermediate group. None of the phoria measures or the measures of depth perception differed significantly between the groups. Of these measures, only error on the depth perception task (expressed in absolute

Table 1: Mean acuity, phoria, and depth perception scores for the expert, intermediate and novice groups. (ANOVA statistics are derived from one-way comparisons of the groups on each measure).

Measure	Group Experts (n=7)	Intermediates (n=7)	Novices (n=15)	ANOVA Comparison F=[a]
Acuity[b]				
Far Distance				
Binocular	0.97	1.08	0.95	1.746,p>.05
Right Eye	1.04	1.15	1.07	0.749,p>.05
Left Eye	0.98	1.19	1.03	2.374,p>.05
Near Distance				
Binocular	0.84	1.02	0.88	3.497,p<.05
Right Eye	0.88	1.13	0.95	3.039,p>.05
Left Eye	0.98	1.06	0.92	1.564,p>.05
Phoria[c]				
Far Distance				
Horizontal	1.50 eso	2.90 eso	2.06 eso	0.483,p>.05
Vertical	0.39 RH	0.12 RH	0.17 RH	1.402,p>.05
Near Distance				
Horizontal	2.50 exo	1.93 exo	2.60 exo	0.052,p>.05
Vertical	0.23 RH	0.03 LH	0.08 LH	1.873,p>.05
Depth Perception[d]				
CE	0.36	−0.07	0.17	0.149,p>.05
AE	0.42	0.42	1.03	1.162,p>.05

[a] Degrees of freedom = 2,26 for all comparisons; F_{crit} at α=0.05 is 3.370.

[b] measured as visual angles in '

[c] measured in prism diopters

[d] measured in cm

rather than directional terms) showed the expected better mean performance by the expert and intermediate group relative to the novice group. The tests of colour vision revealed colour vision defects, of a mild nature, in only one of the subjects; a novice. The measurement of hand and eye dominance relationships revealed a preponderance of unilateral dominance in all three groups. In those cases in which ocular dominance was clearly developed unilaterality (same side eye and hand dominance) was apparent in 4 of 5 experts, 6 of 7 intermediates, and 10 of 12 novices. A non-parametric analysis of contingencies found no significant differences in the distribution of unilaterality and cross-laterality between the different skill groups ($\chi^2(2) = 0.071$, $p > 0.05$), although this analysis must be treated with caution given the small cell sizes.

Discussion

Although the standard optometric screening tests reveal a minimal number of uncorrected visual defects in the expert and intermediate groups it is apparent from the comparisons with the novice group that experts are not characterized by superior vision, at least as assessed from standard optometric tests. The only significant effect obtained from the 12 measures derived from the three skill groups was a poorer performance by the intermediate group on the binocular near acuity test, although the same mean trend was evident in all the acuity measures. As acuity is adversely affected by age, the older mean age of the intermediate group, rather than any skill-related effect, is the probable cause of this inter-group difference. The observed absence of a systematic expert-novice discrimination on the acuity parameters is consistent with Christiná, Feltz, Hatfield, and Daniels' (1981) study of elite and sub-elite rifle, pistol, trap, and skeet shooters. The only task which showed a trend, albeit a non-significant one, for superior performance by the expert and intermediate players over the novices was the depth perception task (with performance measured in terms of absolute error). Interestingly the use of the Howard–Dolman method over a 3.66 m test distance rather than the use of standard optometric slides to assess depth perception makes this measure arguably the most sport–specific of the battery utilised. Landers at al. (1986), using the standard depth perception slide within the Bausch and Lomb Ortho–rater, have previously found, surprisingly, that depth perception capability assessed via slide is significantly, but negatively, correlated with archery performance. Comparison of these results with the current results strengthens further the case for sport–specific test items.

The absence of greater unilateral dominance for the expert group in comparison to the lesser skilled groups in this study of a static aiming skill is consistent with the observations of Landers et al. (1986) on archers but inconsistent with earlier work on rifle and pistol shooters in which a unilateral dominance advantage was observed (Christina et al., 1981; Daniels & Landers, 1981; Landers et al., 1980). In 'open' skill activities involving striking moving objects, such as baseball batting or playing tennis, propositions have been advanced for a cross–lateral advantage (such a configuration placing the dominant eye closest to the oncoming ball) (Adams, 1965; Baughman, 1968), but the majority of empirical studies indicate that both dominance types are common even at international level competition (Whiting & Hendry, 1968).

The findings on ocular dominance are therefore in line with those on acuity, phoria, and depth perception in arguing against the early assertions by sport scientists (e.g., Graybiel et al., 1955; Miller, 1960; Winograd, 1942) and continuing assertions by sports optometrists (e.g., Revien, 1987; Stine et al., 1982), about the value of these parameters in discriminating experts from novices. Our observations here on the non–

discriminatory power of standard optometric tests of visual functioning are consistent with the growing view in cognitive sport psychology (e.g., Abernethy, 1987; Starkes & Deakin, 1984) that expert sport performance is more a function of a processing strategies (or 'software') advantage than a general sensory advantage arising from the physical capabilities ('hardware') of the receptor systems. Along with the findings of Landers et al. (1986), the current demonstration of the non-discriminatory power of standard optometric tests for 'closed' skill sports in which static aiming predominates is important because it is these static performance conditions in which the standard tests may have been expected to be of greatest utility. If expert billiards and snooker players are not characterized by 'super' vision then the nature of the expert advantage must lie amongst one or more subsequent stages in the information processing sequence. The next two sections describe sport-specific perceptual and cognitive tests which attempt to isolate the locus of the expert advantage.

SECTION 2: SPORT-SPECIFIC PERCEPTUAL MEASURES

A fundamental question in the study of expertise in any domain is whether experts and novices perceive the same things when they view a specific task. Given the essential differences between 'looking' (implying simple visual fixation on a display item) and 'seeing' (implying active information pick-up from the display) (Adams, 1966) an important step toward defining expertise in a particular activity would appear to be to ascertain if experts differ from novices in the information they encode, the patterns they recognize, the speed with which they pick-up information, and the level to which they encode, retain and retrieve information. Since the work of de Groot on expertise in chess, conducted in the 1930s but first published in English in 1965, cognitive psychology has maintained an active interest in these questions of expert perception (e.g., Newell & Simon, 1972; see Gilhooly & Green, 1988, 1989; and Glaser, 1987 for reviews). This interest has been fuelled recently by the advent of expert systems to cognitive science (Duda & Shortliffe, 1983; Posner, 1988). Examination of parallel issues in sport skills has occurred only within the past decade and has proceeded largely by adaptation of the established paradigms from cognitive psychology (see Allard & Burnett, 1985 for a review).

De Groot (1965) allowed five Grandmaster and five lesser skilled chess players 5 s to view a chess board containing from 20 to 24 pieces and then required the players to reconstruct the situation on an empty board. When the original placements of the pieces were from actual game situations the Grandmasters could reconstruct the positions almost perfectly (91% correct) whereas the lesser skilled players made many more errors (only 41% correct on average). However when the same number of pieces were randomly arranged on the board the recall performance of the experts fell to that of the lesser skilled players. Perceptual expertise in this activity, at least, is a consequence of the expert's superior encoding of familiar pattern information and not apparently a function of a greater memory capacity for individual items. In replicating these findings, Chase and Simon (1973a, 1973b) argued that, like the novices, experts are restricted to a short-term memory span of some seven familiar units or "chunks" of information (after Miller, 1956) but that in perceiving familiar patterns (as in the case of the game situations) the basic organizational units or "chunks" used by the experts are larger and richer in detail than those used by the lesser skilled. Evidence of equal information pick-up from shorter duration glances in a reconstruction task was used to support this pattern recognition hypothesis.

A more general version of the pattern recognition hypothesis for perceptual expertise (Simon & Gilmartin, 1973) posits that patterns are encoded into short-term memory as a set of "chunks" (or pattern labels), where comparison is made to known patterns stored in long-term memory. According to this view pattern recognition proceeds through a discrimination net organized around the location of highly salient pieces and experts perform this recognition process better than lesser skilled performers because they possess a larger discrimination net incorporating a large number of different patterns. Storage of 500 to 5,000 patterns in the long term memory of computer programs may be sufficient to simulate the pattern reconstruction performance of expert chess players (Holding, 1985). Demonstration of expert superiority on pattern recall tasks but not on perceptual classification tasks (Saariluoma, 1985) is consistent with this view of expert performance, although evidence demonstrating preservation of the expert advantage when interpolated tasks are added to cause interference to short-term memory processing (Charness, 1979; Frey & Adesman, 1976; Garland & Barry, 1990) suggests that short-term memory is not the locus for expert pattern recognition. The lack of interference from interpolated tasks is more consistent with a levels of processing view of memory (e.g., Craik & Lockhart, 1972; Craik & Tulving, 1975) than with the traditional duplex theory (e.g., Atkinson & Shiffrin, 1968), suggesting that the experts' advantage is in terms of a deeper, perhaps semantically-based, and more rapid encoding rather than a superior ability to retain information in a short-term, limited capacity store. This view is supported by evidence demonstrating that the pattern recall of players is further enhanced if players are given information about the moves preceding the development of the current match position (Frey & Adesman, 1976).

Expert's superiority in recalling rapidly presented information from their domain of interest is a generalised and robust phenomena, holding not only in chess (Charness, 1976; Lane & Robertson, 1979) and other games such as bridge (Charness, 1979; Engle & Bukstel, 1978), GO (Reitman, 1976) and Othello (Wolff, Mitchell, & Frey, 1984), but also in activities as diverse as reading electronic circuits (Egan & Schwartz, 1979), music (Halpern & Bower, 1982; Sloboda, 1976), architectural plans (Akin, 1980) and lines of computer code (Adelson, 1981; McKeithen, Reitman, Rueter, & Hirtle, 1981). In applications of this paradigm to sport tasks, Allard et al. (1980) with the sport of basketball, Starkes (1987) with field hockey players, Borgeaud and Abernethy (1987) with volleyballers, and Starkes, Deakin, Lindley, & Crisp (1987) with ballet dancers, have all demonstrated expert superiority in the recognition of structured but no unstructured displays (e.g., patterned offences rather than random warm-up or time-out drills), thus paralleling the expert advantage evident in tasks typically regarded as more cognitive.

In addition to tapping the expert advantage through recall or reconstruction tasks the putatively greater depth of processing by experts has also been demonstrated using resequencing tasks (tasks in which subjects are required to reconstruct a random arrangement of photographed movement sequences; e.g., Vickers, 1986, 1988) and recognition tasks (tasks in which subjects are required to determine whether a given pattern has been encountered previously or not). Recognition performance is generally superior to recall performance because of the additional information available to facilitate retrieval (Reynolds & Flagg, 1977) but performance in both instances may be expected to be proportional to the depth to which the original stimulus material is encoded. In studies of chess (Goldin, 1978) and of bridge (Charness, 1979) highly skilled performers have been shown to outperform lesser skilled performers in recognizing whether given patterns have been previously encountered or not. The evidence on expert recognition superiority is somewhat equivocal, however. While in some instances display structure enhances the recognition performance of experts over novices as expected, in other cases (e.g., Charness, 1981a) no expertise-related differences in recognition performance have been observed. In the limited applications of the recognition paradigm to sport tasks which are available (Allard et al., 1980; Garland & Barry, 1990; Imwold & Hoffman, 1983) superior recognition by expert has been demonstrated, although the expected interaction with display structure has not always been apparent. A general limitation of the existing studies using both the recall and recognition paradigms to examine expert performance is that they do not, as a rule, go beyond demonstration of the perceptual advantage of the expert to detail what specific elements (or "chunks") within the pattern provide the structure upon which information is picked-up (cf. Abernethy & Russell, 1987) nor do they ascertain whether the experts' superior performance on these tasks reflects a fundamental cause of their expertise or merely a by-product of it (Holding, 1985).

Billiards and snooker would appear to provide an excellent setting for the study of pattern recognition and recall as the perception of game structure from the pattern of the balls on the table provides the only avenue through which the player can look ahead to plan a series of shots and hence a large point-scoring break. Unlike some of the other tasks examined to date pattern information in billiards and snooker exists not only with respect to the spatial arrangement of the elements (i.e., the balls on the table) but also with respect to the colour of the elements. In addition to the white cue ball there are 21 other balls on the table at the start of a billiards and snooker game. Fifteen of these are red and the remaining six are yellow, green, brown, blue, pink and black respectively. At the start of the game each ball occupies a specific position on the table. The rules of the game dictate that points are scored by sinking the balls into the six pockets located around the table with different point values assigned to the different coloured balls. The red balls must be sunk first (for a value of 1 point each) and, while red balls remain on the table, coloured balls can only be sunk immediately following the successful sinking of a red. Any red ball which is sunk remains removed from the table while any coloured ball which is sunk with other reds still on the table is immediately returned to its designated position. When all the reds are off the table the coloured balls must also be sunk in the strict order yellow (for 2 points), green (for 3 points), brown (for 4 points), blue (for 5 points), pink (for 6 points) and black (for 7 points). Only at this stage of the game do the coloured balls remain removed from the table (and therefore away from their designated position on the table). The position of the coloured balls, in addition to the spatial configuration of the balls, therefore provides a valuable "anchor" for pattern recognition in this activity.

In this study pattern recall and recognition tasks were given to expert, intermediate, and novice billiards and snooker players to determine (a) if expertise in this sport is dependent upon superior pick-up of display structure and (b), if so, what elements (global spatial configuration or the position of specific local elements) is central to this pick-up of perceptual structure. The latter question was addressed within a recall paradigm using not only unstructured displays but also structured displays presented with uniformly coloured balls (providing global pattern information alone) and normally coloured balls (providing information on the location of specific individual elements or pattern "anchors" in addition to the global pattern information).

Method

Subjects The same seven expert, seven intermediate, and 15 novice billiards and snooker players used in the first experiment were again used as subjects in this experiment.

Apparatus Both the pattern recall and recognition tests involved the presentation of stimulus slides using a Kodak 35mm autofocus slide projector with the duration of slide presentation controlled by a tachistoscopic shutter (Gerbrand Co., Arlington, MA, Model No. 65).

The Pattern Recall Task

Stimulus Materials Fifty–four slides, depicting three distinct types of pattern presentation, were used as stimuli in the pattern recall task. Equal numbers of slides (n=18) depicted structured game situations in which the normal colours were present, structured game situations in which all the balls were of a uniform (red) colour, and unstructured situations in which balls of different colour were present. The structured slides were derived from typical game situations in which all the coloured balls were located on their assigned sports and some of the red balls were still in their starting cluster. These slides varied only in terms of whether or not the coloured balls were represented by their normal colour or replaced by a red ball. The purpose of this manipulation was to retain the global pattern as a potential cue for encoding but to systematically vary the utility of colour as an anchor for pattern encoding. The unstructured slides depicted random arrangements of the balls on the table with the coloured balls positioned away from their normal spots. Slides were taken from different stages throughout the progress of a normal game with the number of stimulus items for recall on any given slide (i.e., the number of balls on the table) ranging from a maximum of 22 to a minimum of 5 (M=12.5). The number of items per slide was equated across the three types of display presentation. All slides were photographed from the same position directly in front of the table and at an angle and height similar to that from which a player would approach the table when about to begin a new break.

Procedures The 54 slides were each presented to the subjects in random order with each slide presentation lasting 5 s. Presentation was via front projection onto a white screen positioned some 3 m forward of the seated subjects. All subjects were provided with a response booklet containing scaled representations of a billiards table and their task, after viewing each slide, was to record on the scaled diagram of the billiards table the position of each of the balls present in each of the stimulus slides. The use of a scaled schematic response was considerably more convenient than using an actual billiards table for the reconstruction and was considered justifiable given that Chase and Simon (1973b) found no difference in recall performance between the two methods. Subjects were not allowed to make any recordings during the 5 s stimulus exposure. A different response sheet was used for each trial and subjects were permitted as much time as they required to record their responses on any particular trial. A colour code legend was provided for the subjects to discriminate the position of the different coloured balls on the table.

Prior to the commencement of the experiment all subjects were provided with a one page description of the basic rules of snooker (including information on the designated positions for the different colours). Subjects were then given basic verbal instructions on the general requirements of the task and were then presented with two trials of practice to familiarise themselves with the response requirements of the task. Following this initial practice and prior to the commencement of the experiment proper subjects were pre-informed that some of the slides would contain red balls only and that the coloured balls would not necessarily be on their assigned spots. The recall task took in all some 50 minutes to administer. All the expert and intermediate subjects were tested together and all the novices were tested together.

Analysis of Data To enable an accurate measure for recall performance to be derived it was necessary to utilise largely manual matching techniques between the subjects' responses and a template containing the correct position of each ball within each slide. This involved the following steps. The correct position and colour of each ball as presented in the slide was first measured and recorded onto scaled diagrams similar to those used by the subjects in completing their responses. Templates were then created on overhead transparencies for each slide with each correct response having a circular band width for error drawn at a distance equivalent to 5% of the total area of the table. This template was placed over the response given by each subject and rotated and/or translated so as to maximize the number of correct responses i.e., to maximize the number of balls correctly placed within the defined error bands. This scoring method was selected because it emphasizes the importance of correct patterns in the task and accounts for situations where subjects have maintained the structural relationships between stimuli but have translated or rotated the pattern away from the actual table co-ordinates.

The number of balls correctly positioned (after template matching) was then recorded and the dependent measure derived was the number of balls correctly positioned expressed as a percentage of the total number of balls in the particular slide. This measure was then subjected to a 3 x 3 (Group x Slide type) mixed factorial analysis of variance.

The Recognition Task

Stimulus Materials A total of 28 slides were presented to the subjects in the recognition task. Half of the slides the subjects had seen previously in completing the pattern recall task and an evaluation task (to be described in section 3). The other slides were new ones depicting slight modifications to situations previously experienced in the recall and evaluation tasks. Of the previously seen slides, seven were randomly selected from the pattern recall task and seven from the evaluation task, with those slides from the pattern recall task being composed of three structured colour slides, two unstructured colour slides and two structured slides represented with balls of uniform colour. The number of balls shown in the slides varied from 5 to 20 with the angle and height of the view of the table identical in all slides.

Procedure Each stimulus slide was presented for 8 s and subjects were required to circle either yes or no in their response booklet to the question 'Have you seen this slide before?'. In addition subjects were required on each trial to respond to the companion question 'How certain are you about your judgment?' by selecting the appropriate point on a 5-point Likert-scale arranged from 1 (Totally Unsure) to 5 (Totally Certain). The 28 slides were presented in random order so as to minimize any order effects. Subjects were given no prior warning while performing either the pattern recall task or the evaluation task that recognition of slides from these tasks would be subsequently tested.

Analysis of Data The percentage of correct responses and the mean confidence ratings were derived as dependent measures and each was subjected to a 3 x 3 (Group x Slide type) mixed factorial ANOVA. The slide type factor had as its three levels new slides, previously viewed recall slides, and previously viewed evaluation slides. As was the case with the analysis of the pattern recall data, the source of significant main effects were determined using the Newman–Keuls post–hoc procedure and significant interactions were further analyzed through analyses of simple main effects.

Results

Pattern Recall Task

Figure 1 plots recall performance as a function of the display structure and colour for the three different skill groups. Display type exerted a significant main effect upon recall performance ($F(2,52)=291.35$, $p<0.001$) with significantly poorer performance for all skill groups on the unstructured conditions (M=56%) than on both the structured conditions with (M=77%) and without (M–78%) information pertaining to colour. In the absence of structure (i.e., when the balls were arranged randomly on the table) the recall performance of all three groups fell to a level where only approximately half of the balls on the table were correctly located in recall. This finding indicates that structure is an essential element for rapid information pick–up in billiards and snooker but that the detection of structure is not directly influenced by whether the display includes colour cues. Although skill level exerted no main effect upon recall performance ($F(2,26)=2.82$, $p>0.05$), skill level did interact significantly with slide type in determining recall accuracy ($F(4,52)=2.86, p<0.05$). Under the structured display conditions in which colour cues were available the recall performance of the expert group was superior to that of the other two groups ($F(2,26)=4.166, p<.05$). No significant skill level effects were evident on the unstructured slides or on the slides showing structured situations with balls of uniform colour.

Recognition Task

Recognition Accuracy Main effects for both expertise and slide type were

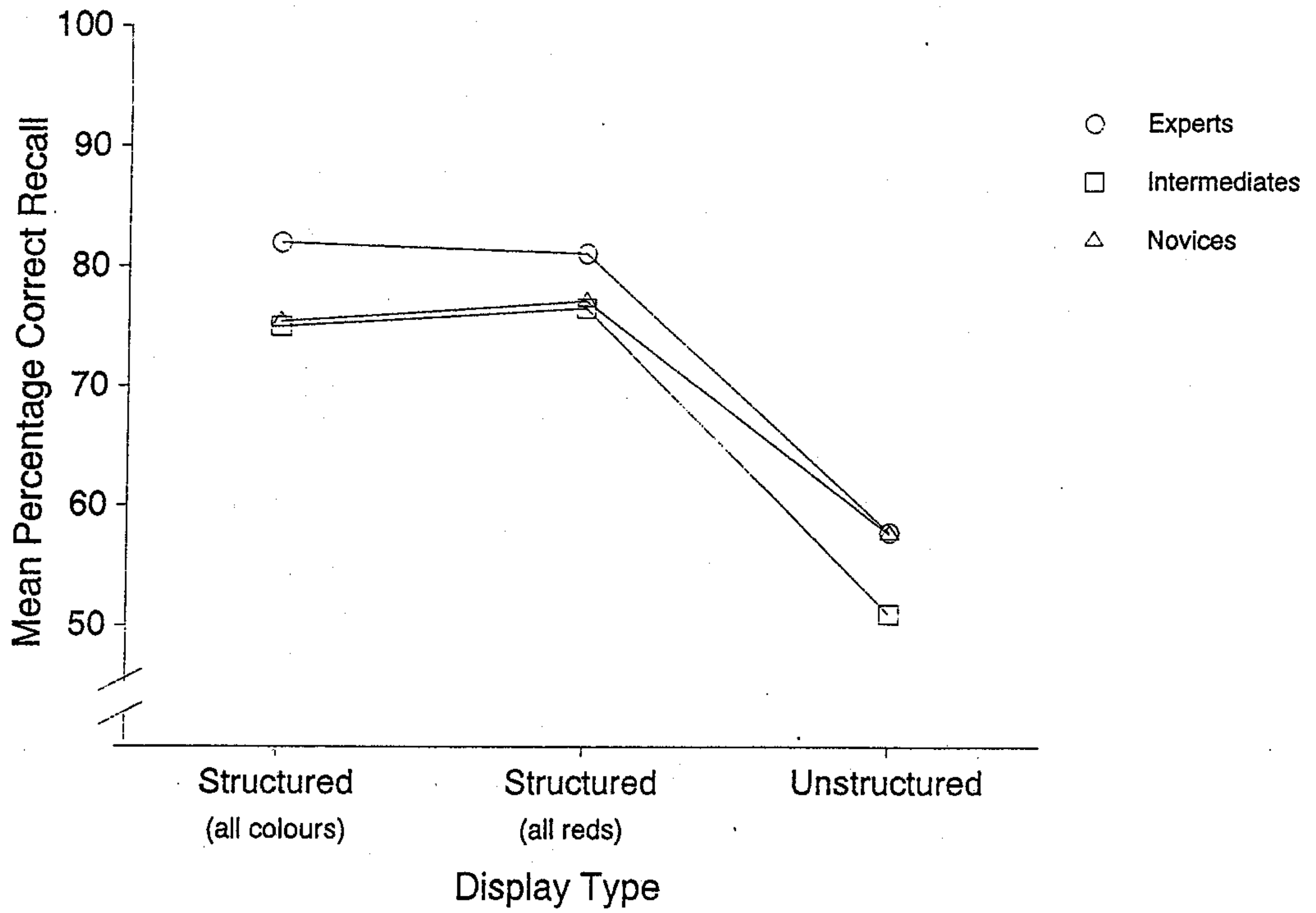
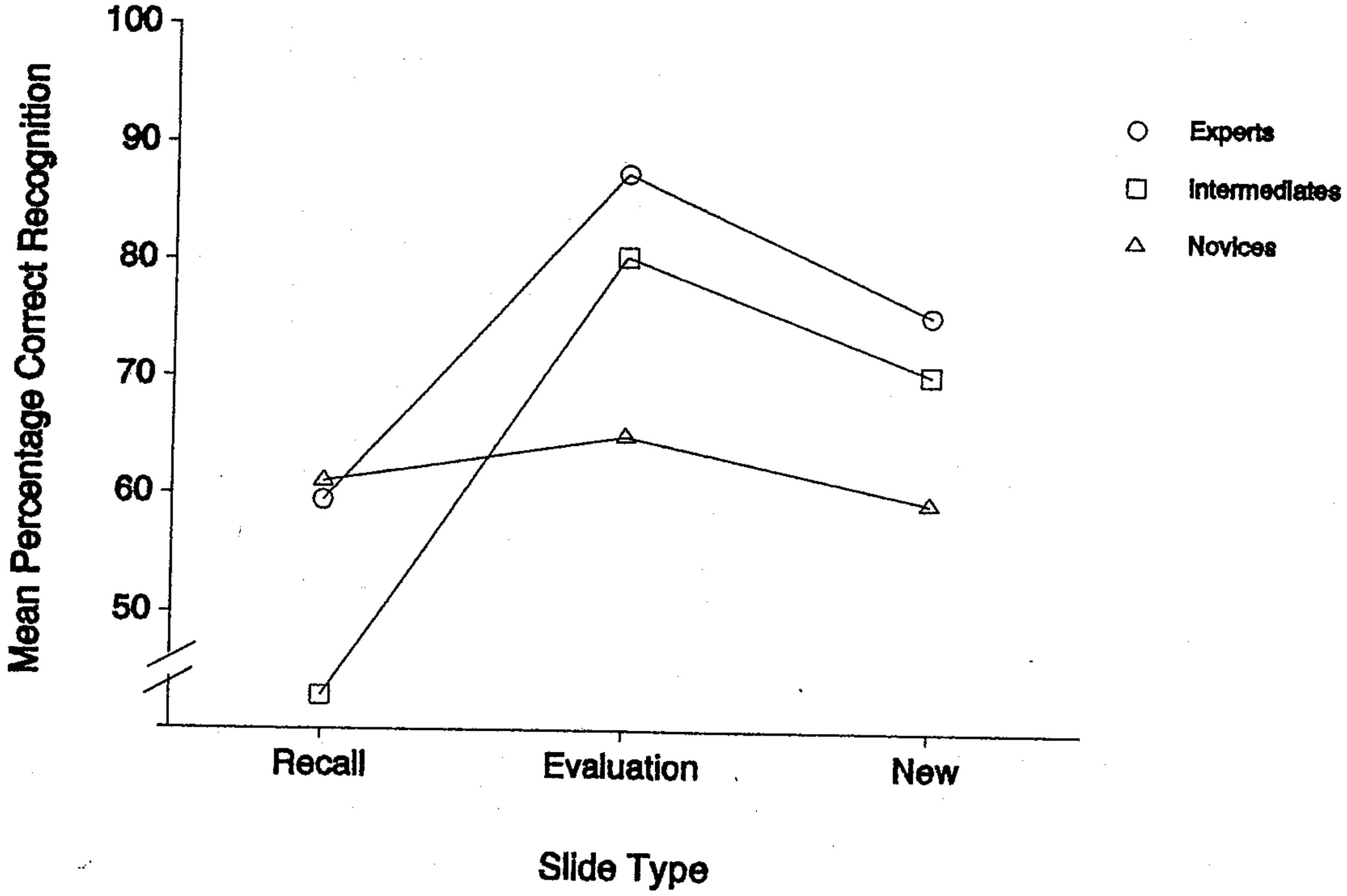


Figure 1: Mean percentage of stimulus items correctly recalled as a function of player expertise and display structure.



<u>Figure 2</u>: Mean percentage of correct recognition judgements as a function of player expertise and slide type.

observed on the percentage of correct responses made in the recognition task (Figure 2). The skill level main effect $F(2,26)=7.27, p<0.01$) resulted from an overall recognition superiority for expert players (M=74% correct recognition) compared to both intermediate level players (M=65%) and novice players (M=62%). No significant differences were observed between the intermediate and novice skill groups. The significant slide type main effect ($F(2,52)=6.48, p<0.01$) was due to greater recognition accuracy for all subjects when evaluation slides were presented (M=74% correct recognition) compared with recall slides (M = 56%). Recognition for new slides (M =66%) did not differ significantly from recognition of either the evaluation or recall slides.

A significant interaction between skill level and slide type was also observed, ($F(4,52) = 2.58, p< 0.05$) with analysis of simple effects for skill level across levels of slide type revealing a skill level effect only on the evaluation slides, ($F(2,26) = 4.43, p<0.05$). Experts outperformed novices but not intermediates in recognizing previously presented evaluation slides. No significant skill level differences were found on the other two slide types. Simple main effects analysis on slide type across levels of skill, revealed significant effects for both the experts ($F(2,12) = 10.43$, $p < 0.01$) and the intermediate level players ($F(2,12) = 12.37$, $p < 0.01$). Post-hoc analyses revealed poorer recognition for recall slides compared to the other slide types for both the expert and intermediate level players. No such effects were apparent for the novice subjects.

Confidence Ratings The mean confidence ratings on the recognition task are presented in Figure 3 as a function of skill level and slide type. A skill level main effect was evident on this confidence measure ($F(2,26) = 11.80$, $p < 0.0001$), with novices showing significantly lower confidence in their recognition judgments (M=3.27) compared to experts (M=3.93) and intermediate players (M=4.13). A main effect for slide type was

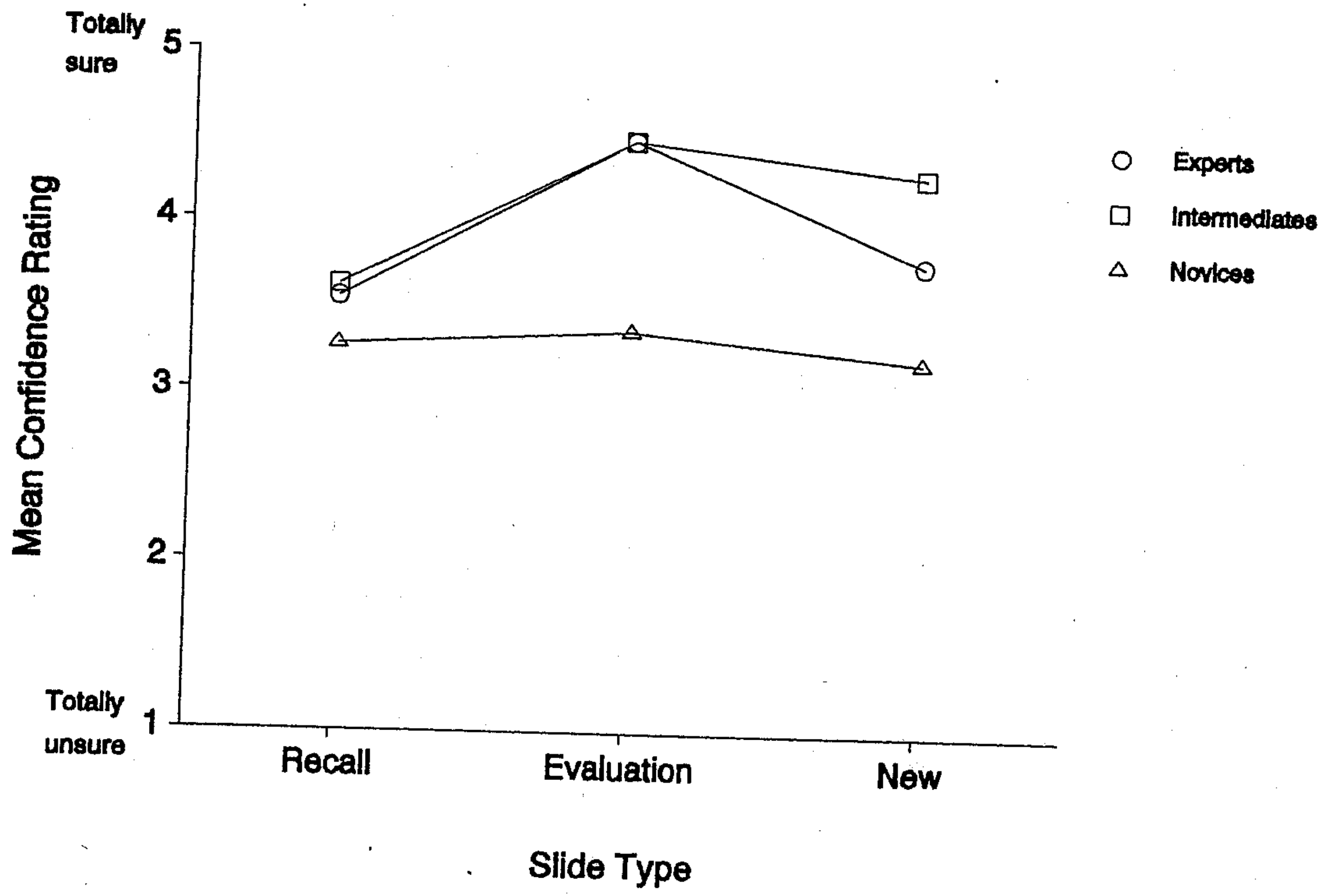


Figure 3: Mean confidence ratings on the recognition task as a function of player expertise and slide type.

also observed ($F(2,52) = 11.28$, $p < 0.0001$) with confidence being greatest when all subjects were presented with evaluation slides (M=3.9), compared to recall slides (M=3.4) or new slides (M=3.6). Each group's confidence in their judgment therefore parallels quite strongly their actual recognition performance (cf. Figure 2).

A significant interaction between skill level and slide type, ($F(4,52) = 4.88$, $p < 0.01$), was also found on the confidence measure and this was due to the intermediate players' lower confidence for recall slides compared to the other slide types, ($F(2,12) = 5.76$, $p < 0.05$) and experts' higher confidence for evaluation slides compared to the other slide types, ($F(2,12) = 14.58$, $p < 0.001$). No simple main effects of slide type were evident for novices. From an analysis of simple effects of skill level, confidence in recognising new and evaluation task slides differed between skill levels. For both these types of slides, novices were least confident in their recognition judgments. No simple effects for skill level were evident on the recall slides.

Discussion

The results from the pattern recall task are consistent with previous studies of perceptual expertise in cognitive (e.g., Chase & Simon, 1973a, 1973b) and sports (e.g., Allard et al., 1980) tasks in demonstrating that the expert advantage exists only for stimuli that provide all the display information normally available to the performer. In the case of billiards and snooker an expert advantage was apparent only when the stimulus materials depicted a spatial arrangement of the balls on the table typical of a normal game situation and used balls of correct colour to specify designated locations on the table. No expert advantage was apparent under display conditions where either the spatial configuration of the balls was randomised or all the balls were of uniform colour, although significant expert–novice differences were approached in the latter condition. When all normal structure was removed from the display by randomising the location of the balls across the table, expert recall performance was reduced to the level of the novices, indicating that the expert's superiority is not a general one related to greater perceptual or memory capacity for materials of all type but is rather a specific one related to encoding and retrieval strategies for patterns unique to billiards and snooker. Such a finding is consistent with a levels of processing approach (e.g., Craik & Lockhart, 1972) with the greater meaningfulness of typical game patterns to experts facilitating a deeper encoding and selective recall superiority for these stimulus patterns alone.

For all three skill groups using randomized rather than structured stimulus patterns impaired performance to the point that the location of only approximately half of the balls on the table could be recalled. This suggests only minimal exposure to the game and its rules (such as provided by the instructional set used in this experiment) is sufficient to provide a knowledge base which is of use in facilitating the encoding and recall of the pattern which exists within game displays. Recall in the structured conditions was aided by the coloured balls (or red substitutes) occupying their designated positions on the table and by way of the patterns containing a cluster of reds in positions displaced minimally from their starting locations. In contrast in the unstructured conditions the arrangement of the balls was completely randomised such that subjects could not encode using any game–based heuristics and were therefore forced to revert to encoding individual item positions or, at most, simple relationships between items (e.g., a cluster of two or more balls positioned together near the centre of the table).

Removing the coloured balls and replacing them with balls of uniform colour had no significant influence on recall performance for any of the skill groups. However although colour per se does not enhance recall performance this does not mean that the normal position of the different coloured balls on the table does not serve as an important anchor for pattern recall. In the structured slides it may be sufficient for the subjects to quickly observe whether there is a ball (regardless of its colour) on the spot normally occupied by each of the colours. In this way knowledge of the normal game structure (in terms of the normal location of each of the coloured balls[3]) may facilitate recall of structured slides over unstructured ones but the actual colour of the ball on each spot normally occupied by a coloured ball may be relatively unimportant, producing no special recall advantage for structured slides containing the normal colours over similarly structured slides composed of balls of uniform colour. Although not significant, the trend in the mean recall scores is for expert performance on the structured slides to improve slightly with the availability of colour information whereas the performance of the novices and intermediates deteriorates slightly when colour information is provided. One possible explanation of this trend is that colour may be an integral part of the normal encoding unit for experts (i.e., patterns are encoded using colour as an anchor) whereas for novices (and intermediates) patterns may be usually encoded in terms of spatial configuration and the addition of colour may create an additional processing dimension and demand that may actually prove slightly detrimental to recall performance.

The expert players's selective superiority in the pattern recall task was mirrored in performance of the recognition task. In keeping with the findings of Allard et al. (1980) on expert and novice basketballers, Goldin (1978) on chess players, and Charness (1979) on bridge players, the expert billiards and snooker players in this study made more correct detections (responding 'yes' to a previously seen slide) and more correct rejections (responding 'no' to new slides) than their intermediate and novice counterparts. As with the pattern recall task the experts' recognition superiority was selective, being most apparent for evaluation slides (i.e., slides for which the subjects had previously been required to make a detailed assessment of the relative advantage of the situation confronting the next player; see next section). Experts showed greater recognition of slides presented previously for evaluation than for slides presented previously as part of the pattern recall tasks whereas novice subjects showed similar levels of recognition for both slide types. As the novices' performance is equivalent across slide types it may be possible to conclude that the experts' superiority on the evaluation task is a function not of the longer original exposure times for the evaluation slides over the recall slides (8 s as compared to 5 s) but of the greater level of processing required at the time of encoding. For experts evaluating the relative strength of a position displayed on a particular slide requires a detailed analysis of options and forward planning whereas recalling the spatial arrangement of the balls in the same slide may need only a quite superficial analysis. The greater level of processing accompanying encoding of the relevant slide provides a plausible explanation of their high probability of subsequent recognition. Novices, perhaps lacking the forward planning and evaluation skills of the expert, may be only able to apply the same superficial level of analysis to the evaluation slides as to the pattern recall slides, thus giving rise to similar recognition performance across all slide types.

The greater level of processing undertaken by experts in comparision to novice players and undertaken by the expert players on the evaluation slides compared to the other slide types is reflected not only in the recognition performances but also in the ratings of confidence made in conjunction with the recognition judgments. This observation on billiards and snooker players directly parallels similar observations on chess players (Goldin, 1978) and indicates that experts have reliable insight (metacognitive knowledge; Brown, 1977) into their own pattern recognition capabilities. An interesting side observation, which runs contrary to Charness's (1981a) observation of an inverse proportionality between age and confidence ratings in chess, is mean ratings of confidence by the older intermediate skill group which are, on average, greater than or equal to that of the younger expert group.

Both the pattern recall and recognition tasks clearly demonstrate that experts and novices do not see the same things in physically identical displays. Expert billiards and snooker players show a clear advantage in performing perceptual tasks which are sport-specific rather than general in nature and the experts' advantage on these tasks is generally consistent with a levels of processing explanation. It is important to note however that the selective superiority of the expert players on the recall and recognition tasks is not necessarily proof of the pattern recognition hypothesis of expertise proposed by Chase and Simon (1973a, 1973b). Indeed a number of strong arguments can be presented that the superior performance of experts on tasks like those used here may be more a function of a cognitive than a perceptual or memory advantage and that expertise differences may still exist on occasions in the absence of skill-related differences in memory performance (Holding, 1985; Holding & Reynolds, 1982). The fact that experts see things differently to novices (see also Lesgold et al., 1988) may be a consequence of an underlying cognitive advantage (Glaser & Chi, 1988) and this possibility is supported by the persistent observation that, as in perceptual tasks, the experts' advantage in tasks assessing knowledge and other elements of cognition appears to be domain-specific and not generalizable across domains (Voss & Post, 1988)[4]. Some possible cognitive bases of expert performance in billiards and snooker are examined in the next section.

SECTION 3: SPORT-SPECIFIC COGNITIVE MEASURES

One favoured approach to examining the cognitive aspects of expert performance involves the use of structured interviews and questionnaires which attempt to explore the breadth, depth and diversity of the knowledge base performers have developed about a particular activity. A number of fundamentally different types of knowledge have been proposed in the literature including declarative knowledge, which is knowledge about factual information, conceptualized to be organized in the form of a propositional network, procedural knowledge, which is knowledge pertaining to how to do something within a particular domain (i.e., knowledge of rules and concepts used to produce patterns of action) and strategic knowledge, which is knowledge of rules, concepts and strategies of a generalizable form applicable across a number of different domains (Anderson, 1981, 1982; Chi, 1981).

Clear differences have been demonstrated in the nature of the knowledge bases available to experts and novices. In domain-specific settings experts have been shown to have access to a more complete and highly differentiated store of both declarative and procedural knowledge than novices (Adelson, 1984; Chi, 1978; Chi, Feltovich, & Glaser, 1981; Chiesi, Spilich, & Voss, 1979; Gobbo & Chi, 1986; Johnson at al., 1981) with these knowledge-based differences persistenting equally strongly in sport tasks as in tasks traditionally classified as verbal-cognitive (French & Thomas, 1987; McPherson & Thomas, 1989; Thomas, French, & Humphries, 1986; Thomas, French, Thomas, & Gallagher, 1988; Thomas & Thomas, in press). Undoubtedly in part because of their greater procedural knowledge experts are able to see and represent problems within their domain of expertise at a deeper, more principled level than novices, solving problems through the use of concepts, semantics, and principles rather than through reliance on superficial, syntactic elements of the problems (e.g., Chi et al., 1981; Chi, Glaser, & Rees, 1982; Weiser & Shertz, 1983). The nature of problem-solving appears to shift to this deeper level of analysis as a more detailed and richly structured knowledge base, organized using abstract rather than literal features (Chi, 1985; Garland & Barry, 1990), is acquired (Schoenfeld & Herrman, 1982). Tests of the knowledge bases of experts in cognitive activities like chess may provide better predictions of skill level than perceptual and memory tests of the type employed in the previous section (Pfau & Murphy, 1988).

Another approach which is commonly used to tap the cognitive strategies of expert performers involves the thinking-aloud paradigm in which performers are required to verbalize their cognitions while performing problem-solving tasks from within their particular domain. Studies using this protocol have demonstrated that experts typically spend a great deal of time when first confronted with a problem in attempting to understand the problem qualitatively by building mental representations or models of the problem which define the situation and its constraints (Paige & Simon, 1966). Novices either attempt to solve the problem at a superficial level without initially creating appropriate mental models (Glaser & Chi, 1988) or, in the case where a qualitative analysis of the problem is attempted, the necessary inferences for resolution of the problem are frequently not made (Chi et al. 1982). Experts searching for the correct move in chess show a depth, breadth, and speed of search which is superior to that undertaken by lesser skilled performers i.e., they consider more alternatives, think more moves in advance and evaluate the available options more rapidly than do novices (Charness, 1981b; Holding & Reynolds, 1982). Experts are also typically more forward looking in their attempts to arrive at solutions to problems (at least physics problems; Larkin, McDermott, Simon, & Simon, 1980) than are novices.

An essential adjunct to successful forward planning is the capability to evaluate accurately the effect of alternative response options; poor evaluation having the potential to negate detailed advance planning (Pearl, 1983). In a study of chess players which is of particular relevance to the present study, Holding (1979) observed that superior chess players were better able to discriminate on a 10 point scale the relative advantage/disadvantage that given game positions presented. A wider range of the rating scale was also utilized by the expert performers. These differences in evaluative capability may well reflect the different procedural knowledge bases of experts and novices (Gilhooly & Green, 1988).

Although both the knowledge-based and thinking-aloud paradigms are dependent on subjects' self-reporting on their own strategies, and in some instances such reports may be misleading as the performers may not have direct verbal access to their control strategies (Nisbett & Wilson, 1979), the non-time-constrained and cognitive nature of the shot selection decisions which must be made in billiards and snooker would appear to make them suitable for analysis using verbalization protocols (Ericson & Simon, 1980, 1984). As forward planning and evaluation of shot options would appear to be an integral part of billiards and snooker proficiency we examined these capabilities in expert, intermediate and novice players using a thinking-aloud protocol and a more structured evaluation task. Our hypotheses were that the expert players would be characterized by a greater breadth and depth of forward planning and by a greater capability to evaluate and discriminate the relative strengths and weaknesses of different game situations.

Method

Subjects

With one exception the same expert, intermediate and novice billiards and snooker players who completed the general visual tests and the sport-specific pattern recall and recognition tests again participated in this experiment. One of the expert players did not complete the thinking-aloud task.

Thinking-Aloud Task

Stimulus materials and apparatus. A videotaped record of a 1988 Benson & Hedges competition match between two of the world's leading professional players, Steve Davis and Mike Hallett (both of the United Kingdom), formed the basis of the thinking-aloud task. From this videotaped game six key points were selected at which the players were confronted with a large number of shot options. The spatial arrangement of the balls on the table at these crucial points in the game were reproduced onto a full size billiards and snooker table and 35 mm colour slides of these positions were made using a filming position identical to that used for the perceptual tasks. In the first slide 12 reds remained on the table and the score was 12–0 in favour of the player selecting the next option. In the second slide 11 reds remained with the score 25–0, in the third 4 reds remained at 48–25, in the fourth 4 reds remained at 53–25, in the fifth 3 reds remained at 26–53 and in the sixth 2 reds remained at 54–33. The videotaped sequences were shown to the subjects on a Sony PVM-1370QM high resolution monitor using a JVC HR-7600MS video player-recorder and the slides were presented, as for the perceptual tasks, using a Kodak 35 mm autofocus projector.

Procedures Prior to the commencement of the experiment proper the novice subjects were again briefed on the basic rules of billiards and snooker and on the point values of the different coloured balls. The subjects were then shown the video tape of the Davis–Hallett match from the opening break so that the score and developmental sequence of the game was apparent to them. When the first of the selected crucial decision–making points in the game was reached the video tape was paused and a slide presented depicting accurately the position of all the balls on the table. The subject's task at this point was to verbalize their thoughts with respect to what shot they would play if they were faced with the situation depicted on the slide, what options they would consider, what options they would eliminate and what shots they would plan in advance. Subjects were asked to consider the current score as part of the decision–making process. The formalised instructions that were given to the subjects were modified from those used by Wagner and Scurrah (1971) in their study of the cognitions of chess players.

When subjects had completed their verbalisation on the first slide the continuing game development was again shown via videotape until the next critical decision–making point was reached and the next slide was presented. This sequence continued until decision–making at all six key game positions had been thought aloud by the subjects. All of the subject's verbal responses were recorded onto audio–tape for later analysis.

Analysis of Data The following dependent measures were derived for each subject:

(i) the mean time between slide presentation and the commencement of verbalization;

(ii) the mean number of options considered on each occasion (as an indicator of breadth of planning);

(iii) the mean number of shots planned in advance of the current one (as an indicator of depth of planning);

(iv) the maximum number of shots planned in advance (as a subsidiary indicator of depth of planning); and

(v) the percentage of occasions in which the selected option corresponded with that actually selected by the professional players.

Each of these measures was subjected to a one-way analysis of variance on the factor of expertise.

Evaluation Task

Stimulus materials and apparatus. A total of 12 35mm slides were used for the evaluation task. The slides were photographed from the same end table position and camera height as described for the recall and recognition tasks and consisted of three variations of each of four game situations, viz., (i) an early game situation in which all but one of the reds remained on the table (leaving, excluding penalties, a minimum of 72 and a maximum of 147 points in the game), (ii) an early mid-game situation in which seven reds remained (leaving a minimum of 48 and a maximum of 83 points), (iii) a late mid-game situation in which only one red remained (leaving a minimum of 30 and a maximum of 35 points) and (iv) an end game situation in which only the brown, blue, pink and black balls remained for a total of 22 points. Each of the stimuli were presented via a Kodak 35 mm autofocus slide projector with a Gerbrand's tachistoscopic attachment used to restrict exposure time.

Procedures Subjects were presented with each slide for a period of 8 s and their task was to evaluate how advantageous the displayed situation was for the next person to play under conditions (i) where the scores were equal, (ii) the player was 10 points ahead, or (iii) the player was 10 points behind. Ratings of how advantageous the situation was were made for each trial and for each score scenario on a Likert-type scale with 0 indicating extremely disadvantageous, 5 neutral and 10 extremely advantageous. Two practice slides were given prior to the experiment proper.

Analysis of Data Mean ratings were subjected to a 3-way group (3 levels) x game situation (4 levels) x score (3 levels) analysis of variance, with repeated measures on the second and third factors. An analysis of kurtosis was also undertaken to ascertain the relative extents to which the three skill groups spread their evaluative responses across the 10 point response scale or tended rather to cluster their responses around the scale mid points. The smaller the kurtosis score the more spread are the ratings given and the greater is the indication of evaluative discriminability (cf. Holding, 1979).

Results

Thinking-Aloud Task

Table 2 provides the mean scores for the expert, intermediate, and novice subjects on the five dependent measures derived in the thinking-aloud task. No significant differences were evident between the groups in terms of the time taken to commence verbalisation (F (2,25)=1.877, $p > 0.05$), the number of options considered (F (2,25)= 1.227, $p > 0.05$) and concordance with the options actually selected by the professional players (F (2,25)= 2.543, $p > 0.05$). The expert and intermediate groups, however, showed significantly greater levels of forward planning than did the novices both in terms of the mean (F (2,25)= 6.988, $p < 0.01$) and maximum (F (2,25)= 13.650, $p < 0.01$) number of shots planned in advance. The expert and intermediate player groups did not differ significantly on these two measures.

Evaluation Task

Figure 4(a-d) displays the mean evaluation ratings of the expert, intermediate and novice groups as a function of the current score and the game situation (early game, early

Table 2: Mean expert, intermediate and novice group scores from the thinking-aloud task. (Standard deviations are shown in parentheses).

Dependent Measure	Skill Group		
	Experts (n=6)	Intermediates (n=7)	Novices (n=15)
Time to commence verbalization (s)	13.03 (2.39)	12.05 (1.64)	15.62 (5.53)
Number of options considered	2.61 (0.31)	2.76 (0.39)	2.49 (0.40)
Number of shots planned in advance	6.22 (1.67)	6.62 (1.62)	4.56 (1.03)
Maximum number of shots planned in advance	7.67 (2.34)	9.14 (3.39)	4.13 (1.46)
Concordance with professional's selections (%)	47.22 (16.39)	54.76 (18.55)	41.11 (8.61)

or late mid-game or end game).

A group main effect was apparent on the evaluation task with experts (M=6.45) and intermediates (M=6.14), on average, rating situations as significantly more advantageous than did the novices (M=4.77) (F (2,26) = 18.177, $p<0.001$). The expert and intermediate groups' ratings did not differ significantly although the trend was towards experts rating situations as more advantageous than intermediates. A significant situation main effect was also observed (F (3, 78) = 3.466, $p<0.05$) but this effect is a relatively minor one – the late mid-game situation being rated, on average, as slightly more advantageous (M=5.89) than the early, early mid-game, and end-game situations (Ms of 5.35, 5.44, & 5.35 respectively). Both these main effects are overshadowed by a significant group x situation interaction (F (6,78) = 2.249, $p < 0.05$). This interaction, along with the significant main effect for score (F (2,52)= 182.481, $p < 0.001$), due to predictably higher ratings when the player is leading by 10 points (M=6.92) than trailing by 10 points (M=4.04), is illustrated in Figures 4a – 4d. In the early game situation (Figure 4a) the only significant difference is a higher rating by the intermediate subjects compared to the novices whereas in the early mid-game situation (Figure 4b) the significant difference is between the expert and novice groups. In both the late mid-game situation and the end game situation the ratings of both the expert and intermediate group remain significantly higher than those made by the novice group. No three-way interaction was apparent in these rating data (F (12, 156) = 1.025, $p > 0.05$).

When the rating responses made by the expert, intermediate, and novice groups are analysed separately in terms of their distribution characteristics the kurtosis values for the three groups are 1.957, 2.215, and 2.431 respectively. These scores indicate flatter score distributions for the experts than for the novices (Newell & Hancock, 1984) and hence a

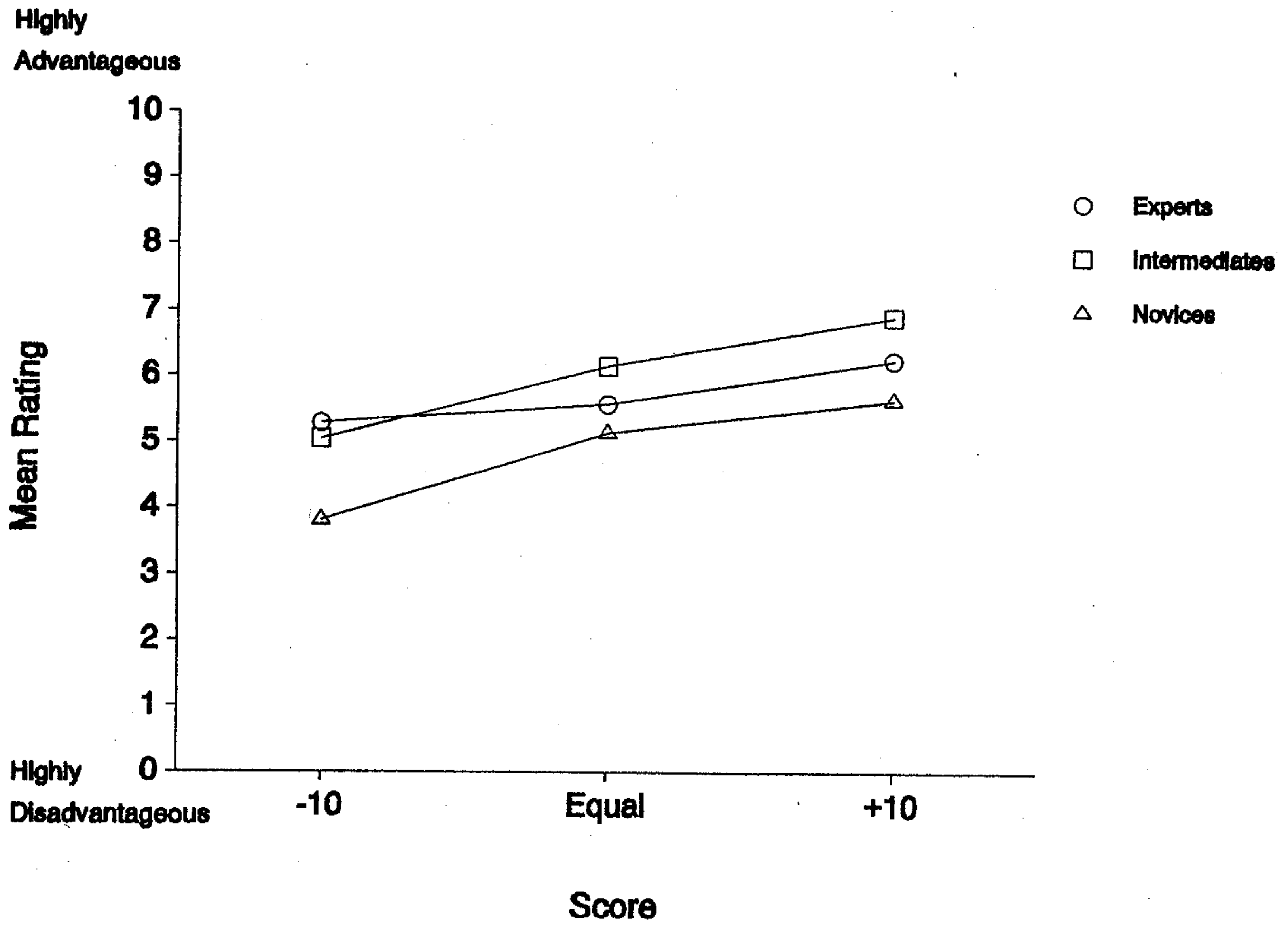


Figure 4(a): Mean ratings of advantageousness as a function of player expertise and hypothetical score situation for an early game situation.

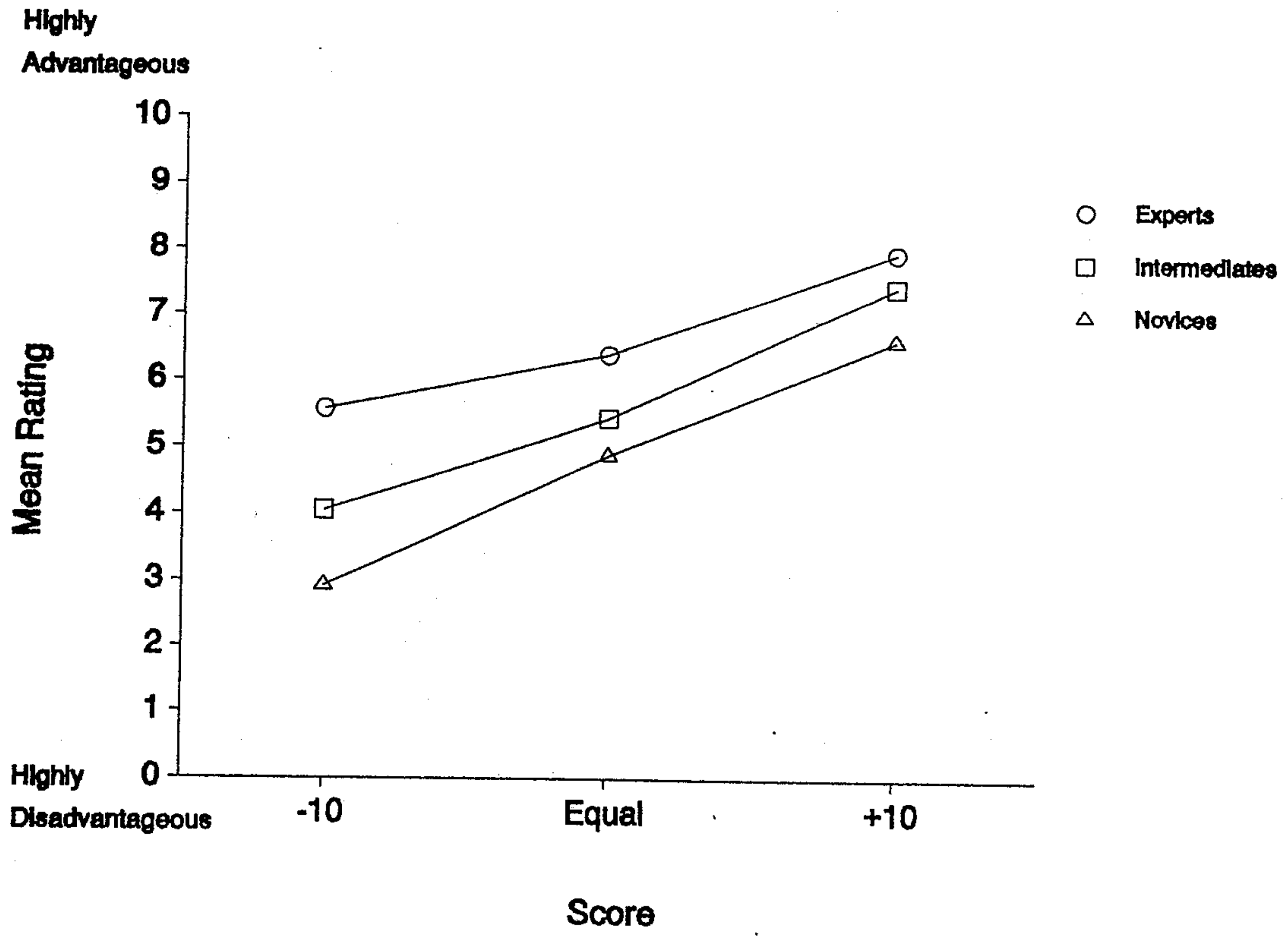


Figure 4(b): Mean ratings of advantageousness as a function of player expertise and hypothetical score situation for an early mid-game situation.

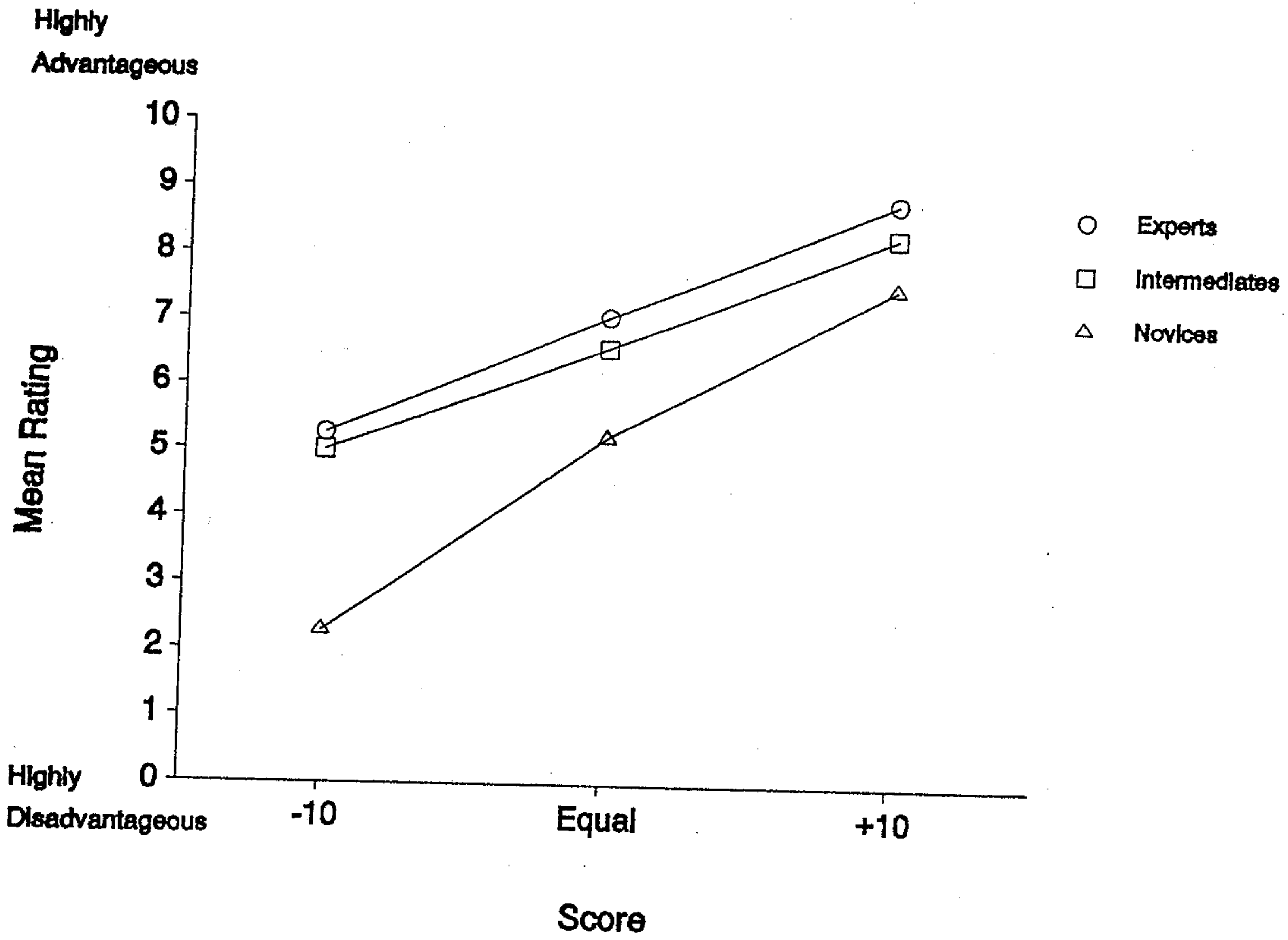


Figure 4(c): Mean ratings of advantageousness as a function of player expertise and hypothetical score situation for a late mid-game situation.

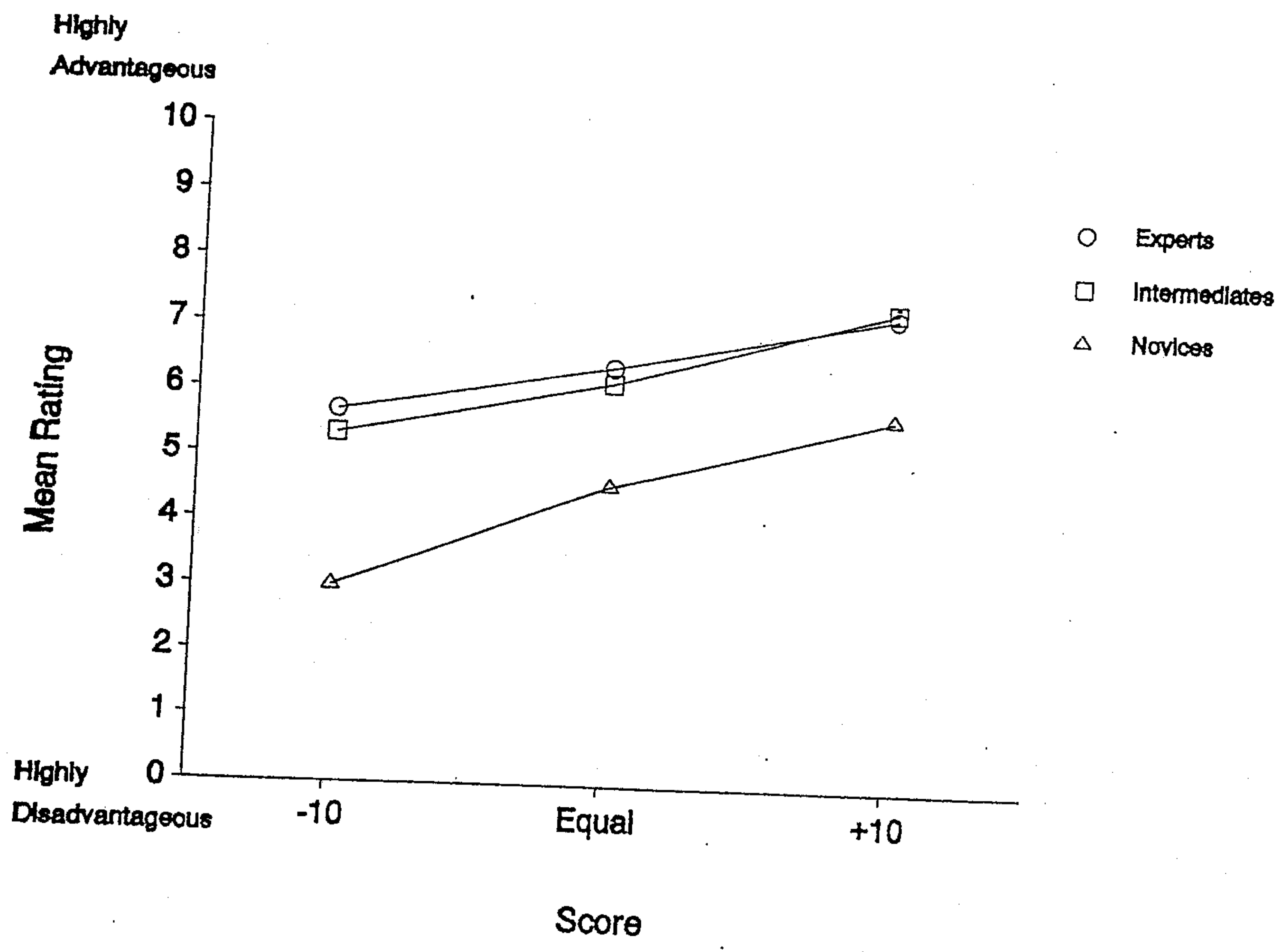


Figure 4(d): Mean ratings of advantageousness as a function of player expertise and hypothetical score situation for an end game situation.

greater spreading of responses across the rating scale for the expert group.

Discussion

The thinking–aloud paradigm indicates that expert and intermediate billiards and snooker players differ from novices in terms of the depth rather than the breadth of their planning. Experts, when faced with shot–selection decisions, examine no more options than novices but those options which they do pursue are followed through to a greater extent than the options chosen by novices. Experts examine options, on average, up to 6 shots ahead of the existing shot whereas novices' forward planning is generally limited to about four shots. The greater depth of forward planning evident in the experts is consistent with the expert cognition revealed in earlier chess studies (Charness, 1981b; Holding & Reynolds, 1982) although these same studies, unlike the present one, also reveal a greater breadth of planning by the experts.

All the groups examined in this study select options which are frequently different from those chosen by the professional players. The low concordance of even the expert's option selections with the shot selections of the professional players is a consequence of the professional player's greater response execution skill. Options that are possible and relatively low risk for the best players in the world would, in many cases, be poor, high–risk shot choices for even the majority of well skilled players. The response latency measure within the thinking–aloud protocol proved to be insensitive to the skill level of the subjects and unable to reveal any differences between experts and novices in the initial formation of mental models or representations of the task (cf. Glaser & Chi, 1988). The response latency measure is necessarily an unreliable one as individual subjects differed substantially in the extent to which they first thought through the available options and then retrospectively verbalized their cognitions as opposed to genuinely thinking–aloud with verbal and cognitive concurrence.

The evaluation task revealed that experts had greater discriminability than novices; expert billiards and snooker players, like their expert chess counterparts (Holding, 1979), making greater use of the full response scale than did the novices. The expert (and intermediate) players were also consistently more positive in rating the advantageousness of given game situations, reflecting not only higher self-perceived capabilities but also a more realistic evaluation of the situations given the number of points remaining on the table. The novice players were inclined to rate a situation as considerably more disadvantageous if they trailed by 10 points regardless of how many points remained on the table (e.g., the novices gave a mean rating of less than 3 when they were 10 points behind even when up to 83 points still remained in the game; Figure 4b). Experts, on the other hand, never gave mean ratings of less than 5 (and therefore never rated a situation as disadvantageous) even when they were 10 points behind with only 22 points remaining in the game (Figure 4d). The score therefore exerts a large influence on the evaluations made by novices whereas both experts and intermediate players give evaluations which are more rational in terms of the points remaining on the table. The expert and intermediate groups' evaluations are therefore more prospectively-influenced (forward-dependent) whereas novices' are more retrospectively-influenced.

Collectively the thinking-aloud and evaluation protocols demonstrate a number of clear cognitive advantages for experts over novices and point to a cognitive as well as a perceptual locus for expert performance. Comparison between the performance of the expert and intermediate group however indicates that it is unlikely that the expert's cognitive advantage over the novice fully explains the expert advantage on perceptual tasks, as some authors (e.g., Glaser & Chi, 1988) have suggested. Experts consistently outperformed the intermediate group on the perceptual tasks (cf. Figures 1 & 2) but, at least on the cognitive measures taken here, the intermediate players are equivalent, or if anything superior, to the experts in the cognitive elements of their performance. Precisely the same elements can not therefore underlie performance on both the sport-specific perceptual and cognitive tasks.

GENERAL DISCUSSION AND CONCLUSIONS

The battery of general visual tests and sport-specific perceptual and cognitive tests which have been applied to the expert, intermediate and novice billiards and snooker players in this study provide some important insight into the nature of expertise in self-paced, static aiming tasks. Consistent with the 'hardware-software' analogy developed for 'open' skill sports by Starkes and Deakin (1984), experts differ from novices in this sport not in their general visual skills but rather in their ability to rapidly encode, recall and recognize structured perceptual information, to accurately evaluate and discriminate the relative strength and weakness of different game situations, and to plan prospectively six or more shots in advance of the current shot. The expert advantage is a sport-specific one which exists in terms of the processing of perceptual and cognitive information and, in keeping with studies of experts from other sports (e.g., Allard et al., 1980; Starkes, 1987) and other domains (e.g., Chase & simon, 1973a, 1973b; Glaser & Chi, 1988; Voss & Post, 1988), this advantage does not appear to be a generalised one or one related to basic visual functioning (cf. Abernethy, 1987). Expert-novice comparisions on a number of sport-specific motor control and motor performance tests are reported in a comparison paper.

Knowing those factors which discriminate the expert from the novice provides a principled basis for training in billiards and snooker and like activities. The current findings suggest, for example, that attempting to improve the performance of players by improving their basic visual skills, for example, may be ill-directed. Visual training programs of the type which have been popularised by optometrists (e.g., Revien, 1987) which use non-sport-specific stimuli are unlikely to be effective in improving sports performance as they do not, as a rule, train the limiting factor to expert performance (Abernethy, 1986; Landers, 1988). Such procedures might be predicted to be effective only if the athlete possesses an uncorrected visual defect which places their general visual functioning below the population norm. In contrast sport-specific perceptual training (e.g., Christina, Barressi, & Shaffner, 1990; Burroughs, 1984 ; Thiffault, 1980) or training which enhances the sport-specific cognitive skills of the performer by either knowledge structure development or modelling of the decision-making trees of experts (e.g. Larkin, 1978) might be expected to be more effective in enhancing the rate of acquisition of expertise because these training procedures address the processing stages known to be important in expert performance. Controlled studies on the effectiveness of different perceptual and cognitive training programs for sports are now a clear priority for sports science as little work is available to draw the essential links between studies on expertise such as this one and the practical demands for effective skill acquisition strategies and training methods for sport.

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Reprint requests should be addressed to Dr. Bruce Abernethy, Department of Human Movement Studies, The University of Queensland, 4072, Australia.

Footnotes

1. The distinction made between perceptual and cognitive tasks is more for organizational than for conceptual reasons. The perceptual tasks to be described here involve a memory component while the cognitive tasks have at least some perceptual element.

2. Previous studies have utilized exposure times from 3 to 8 s depending on the total number of stimulus items to be recalled. With a maximum of 22 balls (stimulus items) within any one slide and an average of 12.5 items per slide, a 5 s exposure time was considered appropriate in the current context.

3. The coloured balls are those other than the reds or the white cue ball which occupy designated postions on the table i.e., the yellow, green, brown, blue, pink, and black ball.

4. Indeed extreme care must frequently be taken to retain the naturalness of the display conditions in order to retain an expert advantage (e.g., see Borgeaud & Abernethy, 1987; Gilhooly, Wood, Kinnear, & Green, 1988).

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MOTOR CONTROL DIFFERENCES BETWEEN EXPERTS AND NOVICES IN A SELF-PACED, STATIC AIMING SKILL

Robert J. Neal, Bruce Abernethy and Craig M. Engstrom

Department of Human Movement Studies
The University of Queensland, Australia

Running Head: Motor Control Expertise

Abstract

The three-dimensional acceleration-time and velocity-time histories of a billiard cue were recorded as six expert, seven intermediate and 14 novice billiards and snooker players attempted to strike either a cue ball or an object ball to a specified finishing position. All subjects performed 20 trials (10 with cue ball and 10 with object ball) under each of two different task conditions - a constant force condition, in which the same finishing position was required for all 10 shots and a variable force condition, in which the required finishing position was systematically and progressively shortened from trial 1 through to trial 10. Acceleration data were collected from a cue-mounted triaxial accelerometer with the time of cue-ball impact determined from a microphone positioned adjacent to the cue ball. Experts differed significantly from novices on the constant force condition but not on the variable force condition. In the constant force condition experts displayed greater trial-to-trial consistency in the cue kinematics and minimized medio-lateral and vertical accelerations, restricting control solely to force applied down the line of the table. All groups showed increased variability in the cue kinematics when the task complexity was increased to include an object ball, although the variability drift was least for the expert performers. In the variable force condition all the skill groups were equally adept (or inept) at modulating impact force on a trial-to-trial basis, control of impact force being principally achieved through control of peak acceleration on the cue during the downswing. No systematic alterations in the duration of either the backswing or downswing of the cue were noted in response to the varying trial-to-trial impact force requirements and no evidence was apparent, for any of the skill groups, of proportional scaling of either the time or force dimensions in the cue kinematics. Some implications of the findings for practice are briefly described.

Motor Control Differences Between Experts and Novices in a Self-Paced, Static Aiming Skill

Despite growing interest in the study of both expertise (e.g., Chi, Glasser, & Farr, 1988) and motor control (e.g., Hollerbach, 1990) by cognitive psychologists there has been surprisingly little hybridization of these research endeavours. Research on expertise has focussed principally on perceptual and cognitive factors (Abernethy, 1987; Allard & Burnett, 1985; Starkes & Deakin, 1984) while research on human motor control has had a predominant orientation toward attempting to understand the foundations of movement control by studying simple limb movements performed by untrained subjects (Whiting, 1982). With the notable exception of isolated pockets of research on expertise in typing (e.g., Gentner, 1988; Rumelhart & Norman, 1982) and piano-playing (e.g., Shaffer, 1980, 1981), there has been surprisingly little research work since the seminal works of Bryan and Harter (1897, 1899) and Book (1908) on the nature of expert-novice differences in the motor control of natural actions. Such a neglect is unfortunate given the potential for expert-novice comparisons to provide a window into fundamental motor control issues (Glencross, Whiting, & Abernethy, in press) and for examinations of motor skills to provide more direct and observable indicators of expertise than can be obtained from studies of cognitive skills (Gentner, 1988).

In this paper we attempt to redress the dearth of study on expert-novice differences in motor control by examining the motor control capabilities and strategies of billiards and snooker players of varying skill levels. Billiards and snooker affords an ideal task setting for the examination of expertise differences in motor control for a number of reasons. First, success in the sport is clearly dependent upon being able to volitionally apply

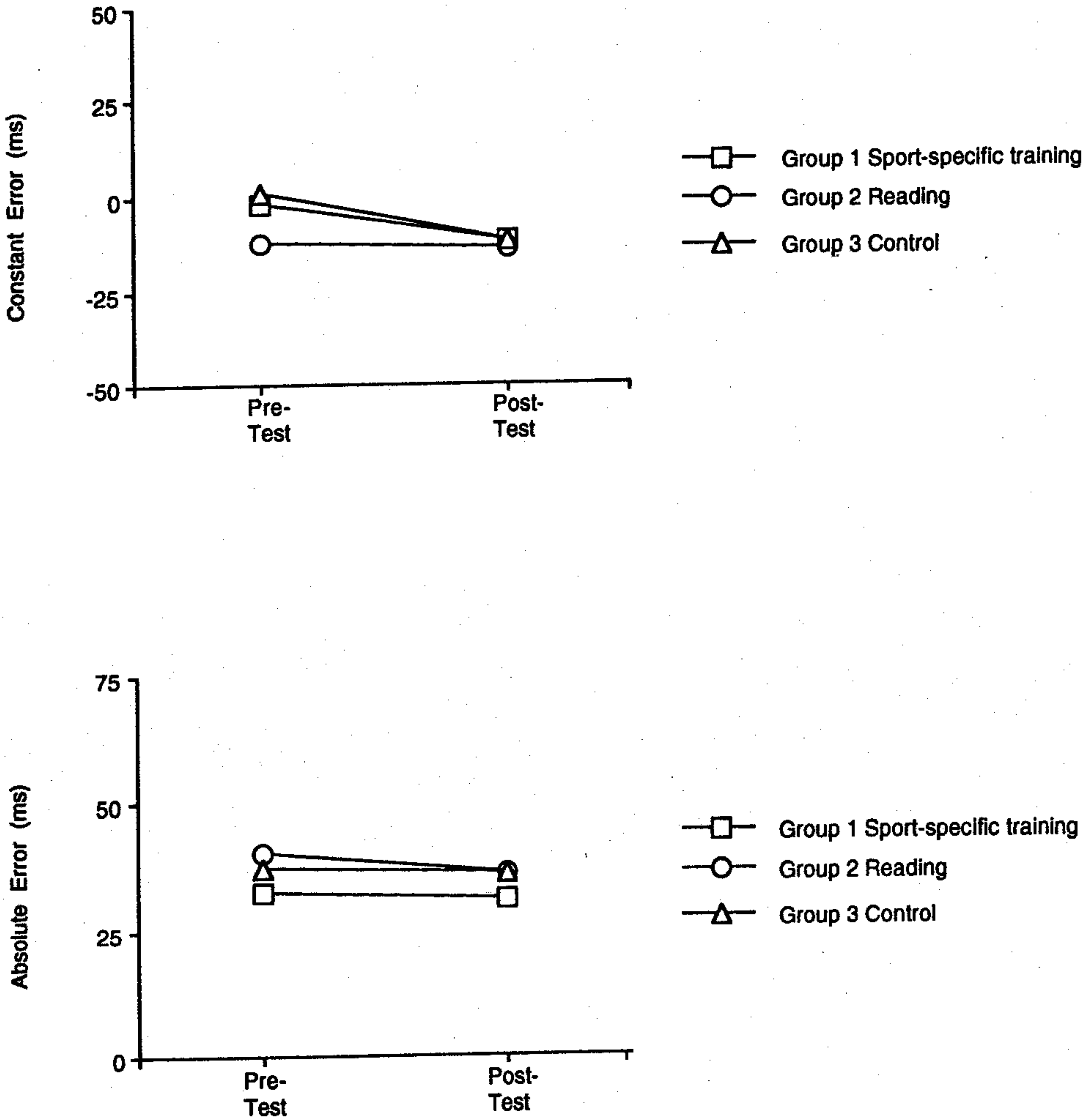


Figure VI.12: Pre- and post-training coincidence-timing errors

Depth perception Depth perception, as assessed from the Howard–Dolman apparatus, followed the same trends as the stereopsis data (Figure V.15). Pre– to post–training changes in depth perception were not significant either overall ($F(1,265)= 0.619$, $p>0.05$) or selectively for any of the groups ($F(2,26)= 0.317$, $p>0.05$).

Reaction time As was the case in Experiment 1, simple reaction time did not change over the 4 week training period either overall ($F(1,26)= 0.214$, $p>0.05$) or for any particular group ($F(2,26)= 0.106$, $p>0.05$). (See Figure V.16). Choice reaction time, however, was subject to a significant main effect of test occasion ($F(1,26)= 7.079$, $p<0.05$) although this effect was not mediated by the type of training experienced by the subjects ($F(2,26)= 0.819$, $p>0.05$). The improvements observed hold for subjects from all three groups and are therefore presumably due to test familiarity effects rather than to the benefits of any visual training undertaken by the subjects. Parallel statistical conclusions to those obtained from analysis of choice reaction time were obtained from the analysis of decision–making rate.

Visual field size Analysis by eccentricity of the static visual field measurements conducted on the Humphrey Visual Field Analyzer systematically failed to reveal the significant group x test interactions needed to support the effectiveness of the visual training intervention program experienced by Group 1. Significant test main effects were obtained at some specific eccentricities (viz., 12° in the left visual field and 12°, 18°, 30° and 66° in the right visual field) indicating some selective test familiarity effects but these effects held across all groups and were not attributable to the visual training regimes practised by subjects in Group 1 (See Figure V.17).

The kinetic field measurements revealed a similar picture (Figure V.18). There was no significant test ($F(1,11)= 0.460$, $p>0.05$) nor group x test = ($F(2,11)= 1.622$, $p>0.05$) interaction obtained on the areas measure, the only significant effect being the one observed previously for stimulus size ($F(1,11)= 98.505$, $p<0.001$).

Peripheral response time The previous analysis of the pre– to post–training changes in performance by Group 1 on the exercises included in their training program revealed significant improvements for this group across each week of practice on the Wayne Saccadic Fixator. The analysis of the pre– and post–training peripheral response times (assessed from the Wayne Saccadic Fixator) of all three groups also revealed the presence of a significant test occasion effect ($F(1,17)= 152.175$, $p<0.001$) overall. Importantly this effect was not mediated by the group membership factor ($F(2,17)= 2.427$, $p>0.05$), indicating that the improvements in performance on the Wayne Saccadic Fixator gained with practice by the group undertaking specific practice on this device did not significantly exceed those improvements in performance gained by Groups 2 and 3 arising simply from test–pretest exposure to the test protocol. The pre– and post–training peripheral response time scores of each group are displayed in Figure V.19.

Eye movement skills As was the case with the analysis undertaken in Experiment 1, analysis of the speed and accuracy data on the King–Devick reading skills task in Experiment 2 revealed only one significant effect –– a main effect for task difficulty on the reading time measure ($F(2,52)= 5.465$, $p<0.01$). There were no significant pre– to post–training improvements in performance time either overall ($F(1,26)= 0.540$, $p>0.05$) or for selected groups ($F(2,26)= 1.777$, $p>0.05$) (see Figure V.20).

finely-graded levels of force in a direct line through the hand-held cue to the cue ball and then onto the target (or object) ball. As force application must be sensitively geared to the required finishing position of both the object and cue balls, the task provides a natural goal-directed analogue to the simple laboratory tasks frequently used to examine individual differences in force control (cf. Keele, Ivry, & Pokorny, 1987). Second, because the striking skill is mechanically quite simple and ,in the main, uniplanar the ideal mechanical model of performance of the task is readily derivable for comparison with actual cue technique. Third, the skill provides natural access to subjects of a wide range of skill levels, with experts trained to a level unable to be matched in novel laboratory tasks. Fourth, as the visual-perceptual and cognitive characteristics of this same cohort of expert, intermediate and novice players is already known (Abernethy, Neal, & Koning, 1991) the addition of motor control data provides the rare opportunity for the development of a comprehensive rather than the typical piecemeal profile of the task expert.

The subjects in this experiment performed striking tasks that required either a consistent response (returning either the cue or object ball to a designated position on the table 10 times in succession) or a finely graded variable response (returning either the cue or object ball to successively shorter finishing positions). Throughout the performance of these tasks the motion of the cue (in three-dimensions) and the dominant arm (in two dimensions) was recorded using concurrent accelerometry and high speed video recording in an attempt to determine how the conflicting control demands of consistency and adaptability (cf. Glencross, 1980) were accommodated by subjects of different skill levels. The subsequent analyses seek to describe the nature of expert-novice differences in pattern consistency and in force modulation in this activity.

Method

Subjects

Six billiards and snooker players ranked within the top 30 in Australia (the expert group), seven intermediate level club players and a control group of 14 novice players participated in the study. The experts (ranging in age from 20 to 45 years and in playing experience from 8 to 30 years) and the intermediates (ranging in age from 12 to 61 years and in playing experience from 1.5 to 45 years) were recruited through the Australian Billiards and Snooker Council. The novices, who ranged in age from 18 to 29 years and who had no competitive experience in billiards and snooker, were university undergraduate students. All subjects were male and naive to the specific purpose of the study. The sample was a sub-group of that previously examined on a battery of visual perceptual and cognitive test items (Abernethy et al., 1991).

Experimental Design and Procedure

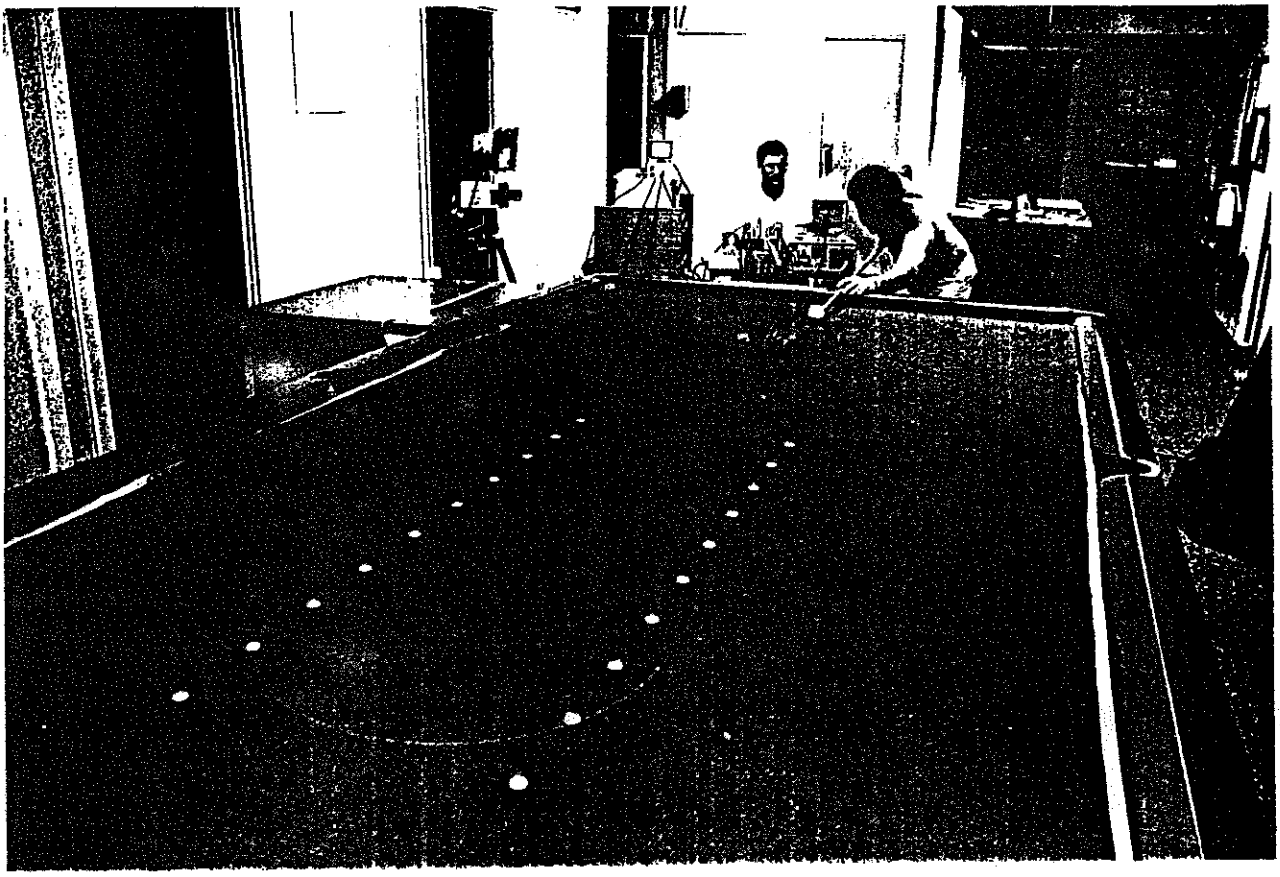
All subjects completed 40 shots (trials) in all –10 trials under each of four different task conditions. The four task conditions consisted of two constant force tasks and two variable force tasks. In the constant force tasks the subject's goal was to either strike the cue ball up the table with the correct force needed to rebound it off the far cushion and bring it to rest precisely in the centre of the table (condition 1) or to strike the cue ball into an object ball located some 40cm directly in front of the cue ball with the correct force to return the object ball to the target position of the centre of the table (condition 2). In these tasks the target force remained identical for all 10 trials within each condition. In the variable force tasks the target position was systematically altered in 18cm steps from a position in the centre of the table on trial 1 to a position 21cm from the far end of the table on trial 10 (Figure 1), with the goal being to modulate the trial–to–trial force applied to the cue ball at impact to leave either the cue ball (condition 3) or an object ball (condition 4) at the required target position. Under all conditions the starting position for the cue ball was its normal spot at the near end of the table.

The order of presentation of the four conditions was randomised across subjects and all subjects were permitted unlimited practice under any of the conditions before the commencement of the experiment proper. On each trial the subjects assumed their normal ready position and executed their customary preparatory routine (usually consisting of some 2–4 preliminary forward–backward movements of the cue). With this completed, the subjects gave a verbal signal to the experimenters upon which data acquisition commenced for a 4s period.

Data Acquisition

On each trial the acceleration–time history of the cue was recorded in three–dimensions using a Kistler Piezobeam triaxial accelerometer attached to the butt end of the cue. In addition, the kinematics of the cue and the player's dominant side upper limb were determined through a high speed video record of the displacement–time histories of retroreflective markers positioned on the cue and the playing side shoulder, elbow, wrist and third metacarpo–phalangeal joints of the subject. Figure 2 provides a general illustration of the experimental set–up.

Accelerometry The accelerometer was so positioned that its Z axis was aligned along the centre of the cue such that accelerations in the Z dimension were down the line of the table in the direction of the shot. The cue was then carefully but comfortably



<u>Figure 1</u>: Target positions for the variable force task. The target position for trial 1 (and for all trials within the constant force task) was the point marked in the centre of the table. The target position for trial 10 was the point closest to the far end of the table.

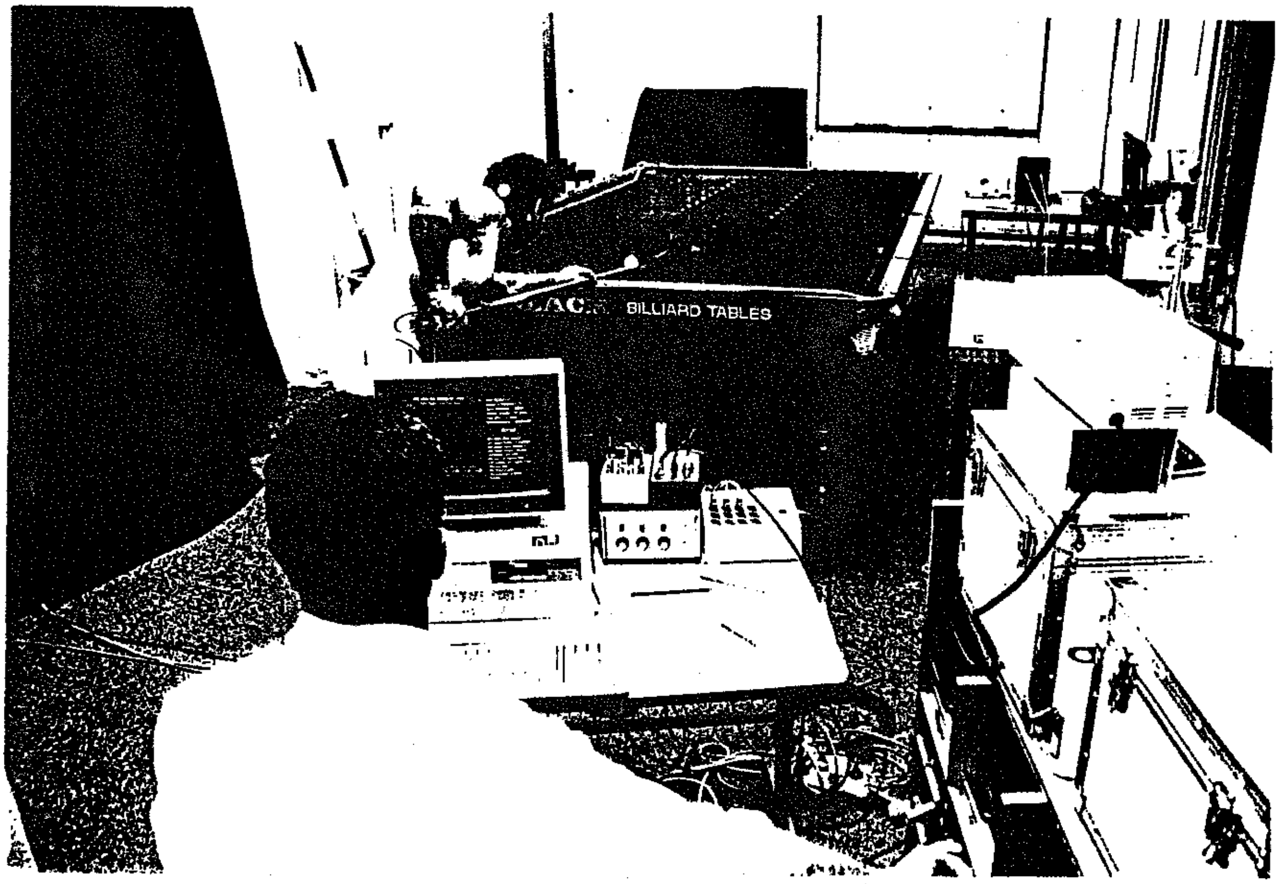


Figure 2: The data acquisition configuration for the experiment.

positioned in the subject's hand on each trial so that its Y axis was vertical (recording accelerations up–and–down relative to the plane of the table) and its X axis horizontal (recording accelerations in a medio–lateral plane across the line of the table) (Figure 3). The output from the accelerometer was passed initially through a coupler and then on to an amplifier. The voltage output from the amplifier was converted to a digital signal (using a Burr–Brown A/D board) at a rate of 200Hz for storage on an IBM–compatible microcomputer. A total of four channels of data were collected on the computer; three channels of accelerometery and an additional channel for recording an electrical signal emanating from a microphone placed near to, and directed at, the cue ball. This microphone detected the sound of the impact of the cue on the cue–ball, causing the voltage on channel four to rise. This same signal was also used to register a high frequency audio–tone onto the videotape record, thus providing a mechanism for synchronising the video and acceleration records. The accelerometer was calibrated using the known acceleration due to gravity.

High speed video A single NAC (60/200Hz) video camera operating at 200 frames/s was positioned to the side of the table some 2.5m from the subject with its film plane parallel to the assumed plane of motion of the cue and upper limb (Figure 2). A 1000 W light was placed next to the camera in order to maximally illuminate the five retroreflective markers and the recorded images were stored for later analysis on VHS tape using a high speed video recorder. A linear scale positioned in the plane of motion was filmed for each subject and used to convert motion on the video image to standard measurement units. Marker motion was automatically digitised using Motion Analysis Corporation Flextrak™ software and displacement–time arrays for each marker were

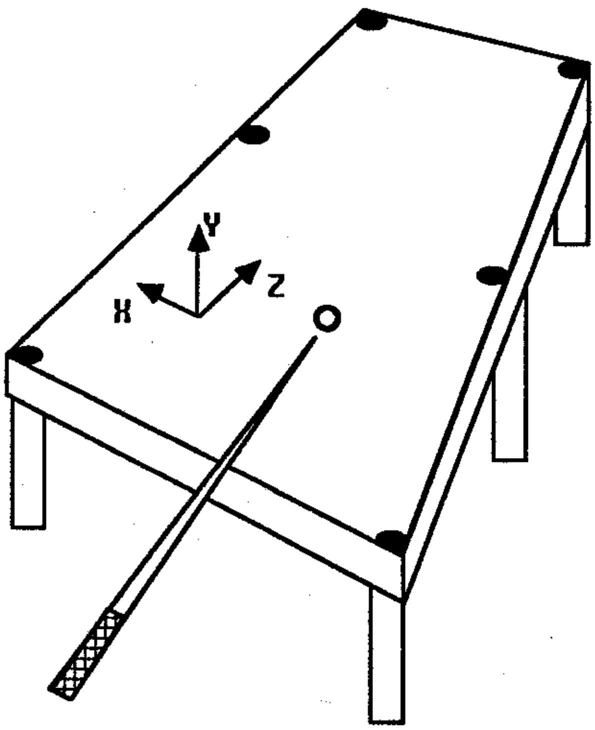


Figure 3: The triaxial orientation of the cue-mounted accelerometer.

recorded after smoothing using a Butterworth digital filter. The video data were used primarily to confirm the Z axis accelerometry values although the potential exists for subsequent quantitative comparison of the upper limb angular kinematics, and hence the stroke technique, of the different players.

Data Analysis

Preliminary data preparation The raw acceleration traces in each dimension for individual trials were first smoothed using a Butterworth digital filter with an optimal cut-off routine (Jackson, 1979). This routine gave rise to typical cut-off frequencies in the 4-6 Hz range. The analysis proper commenced with the Z-acceleration trace for each trial. The impact point was determined from the channel 4 microphone record and its occurrence generally approximated the occurrence of the first zero crossing following peak (positive) forward acceleration (see Figure 4a). The start of motion (SOM) was defined as the first zero crossing retrospective to peak negative (backward) acceleration. The acceleration-time curve was then integrated from SOM through to impact to derive the velocity-time curve for the entire shot (Figure 4b). As the zero-crossing in the velocity profile corresponds with the start of the downswing this was used as a landmark to determine the respective duration of the backswing (delimited by the SOM and the start of the downswing) and the downswing (delimited by the start of the downswing and the point of impact). The time of occurrence of these landmarks in the Z acceleration profile were then used to delimit the periods of analysis within the X and Y acceleration and velocity traces. Separate analyses on both the values at impact and the velocity-time patterns throughout the period from SOM to impact were duly conducted for the constant force conditions (conditions 1 & 2) and the variable force conditions (conditions 3 & 4).

Analyses for the constant force conditions Instantaneous X, Y and Z velocities of the cue at impact were determined and subjected to separate two-way analyses of variance with skill level (expert, intermediate or novice) and task condition (cue ball or object ball positioning) as the factors in the analysis; the latter being a repeated measure. An alpha level of 0.05 was set for this and all subsequent statistical analyses with follow-up simple main effects analyses and Scheffé post-hoc tests being administered where appropriate.

Analyses of trial-to-trial consistency in the velocity patterns in each of the three planes of interest were conducted by first normalising the data from each trial to 100% of the time between SOM and impact using an interpolative spline (de Boor, 1973) and by then calculating the co-efficient of variation (CV) (after Winter, 1988). The CV is effectively the relative standard deviation of the velocity value at each instant in time within the movement averaged over the time course of the movement. The lower the CV the greater is the between-trial consistency in the velocity profile of the cue. The CVs in each plane were then subjected to analyses of variance using the same factors as for the impact velocity measures.

Analyses of the variable force conditions Analyses of impact velocity and of the whole velocity-time profile from SOM through to impact were conducted for the variable force conditions using similar but not identical methods to those used for the constant force conditions. Evidence for direct modulation of force in response to the altered target positions from trials 1 to 10 was examined by determining velocity in the Z direction at impact for each trial and then subjecting this measure to a 3-way analysis of variance.

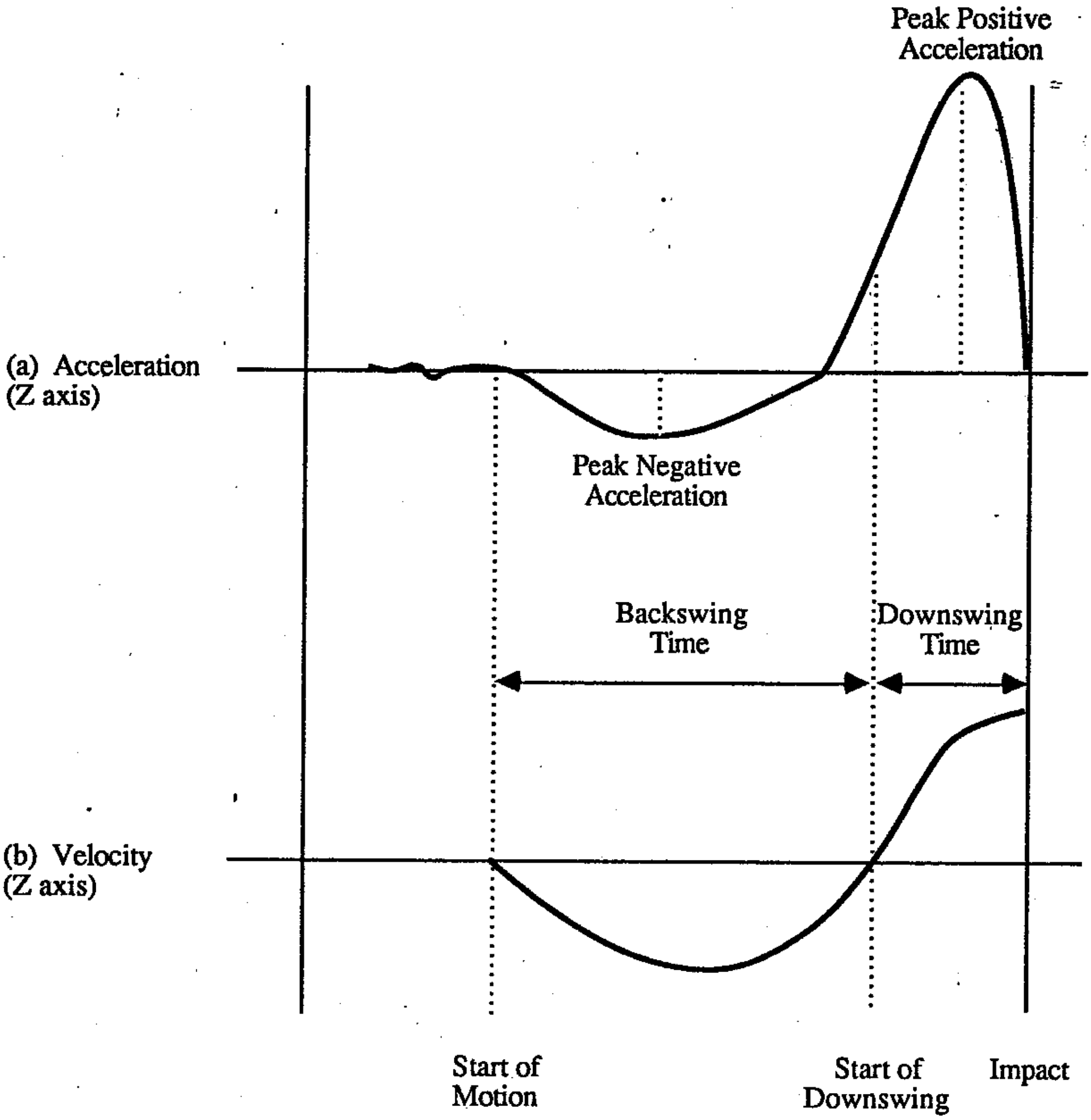


Figure 4: Derivation of the SOM, downswing time and impact measures from (a) the acceleration–time and (b) the velocity–time profiles of the cue.

The factors of skill level and task condition were as for the constant force condition analyses with the additional factor being impact force requirement. Three levels of this factor were subjectively formed by grouping trials 1–3 into a 'hard' impact force requirement sub-condition, trials 4–7 into a 'medium' sub-condition and trials 8–10 into a 'soft' sub-condition. Skill groups capable of finely controlling impact force would be expected to show significant impact velocity differences in the Z direction between the 'hard', 'medium' and 'soft' sub-conditions.

As a second test of force modulation Pearson product-moment correlations were calculated between impact velocity in each of the axes of measurement and trial number. Given that a proportionate reduction in cue force at impact is required as trial number increases from 1 to 10 in order for the subjects to adapt successfully to the changing task demands, the higher the negative correlation between impact velocity in the Z direction and trial number the more sensitive must be the subject's force output control (Figure 5). The correlation co-efficients in the Z dimension were computed independently for each subject under each task condition and were then subjected to 2-way (skill level x task conditions) ANOVAs.

The analyses of the complete acceleration-time and velocity-time patterns from SOM through to impact in the variable force conditions involved independent assessments of the relative and absolute changes in the amplitude (acceleration & velocity) and duration (time) dimensions of cue kinematics made by the subjects in order to accommodate the trial-to-trial variations in task demand. Possible changes in the

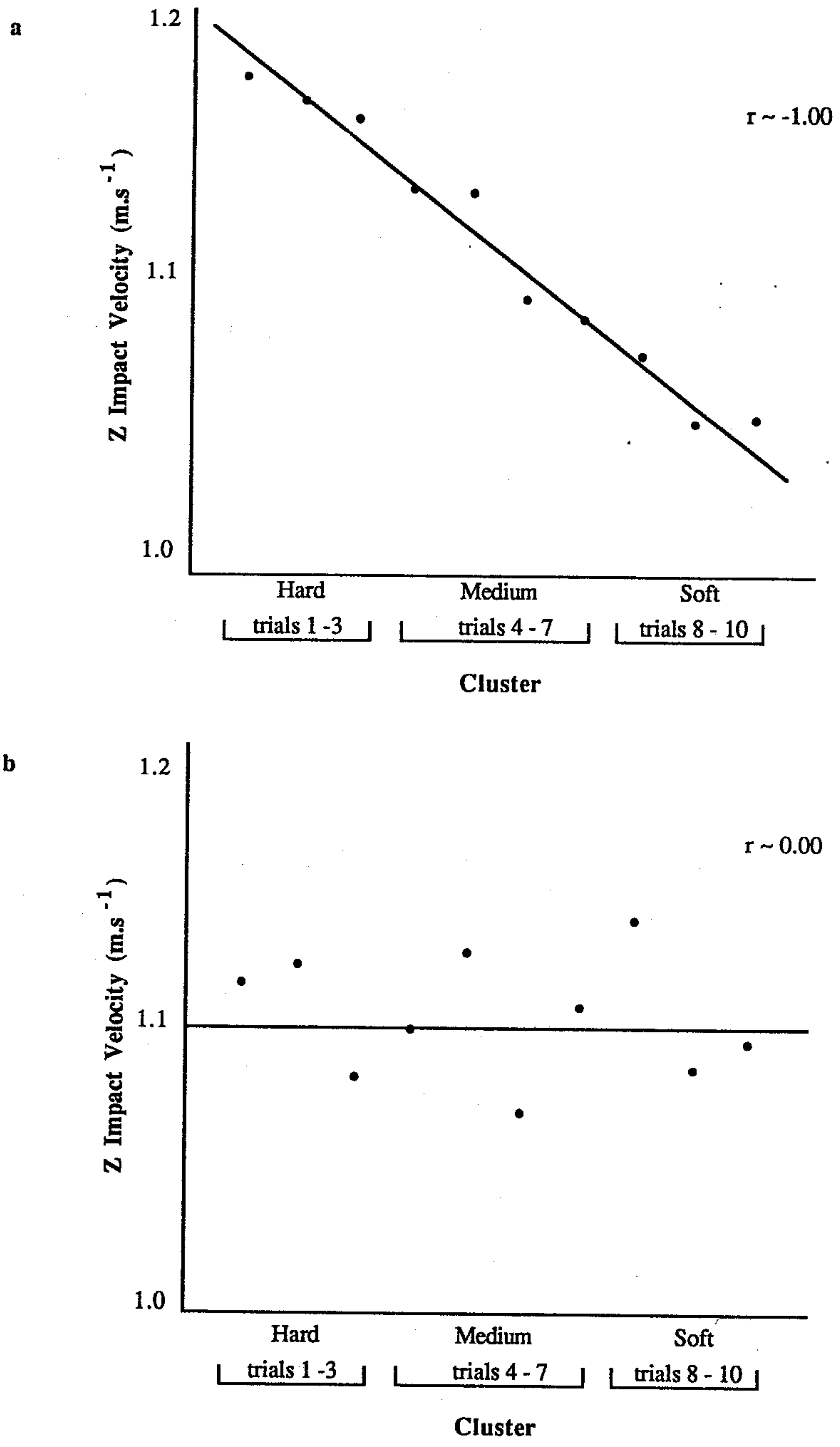


Figure 5: Expected correlations between Z velocity at impact and trial number for subjects with (a) sensitive and (b) insensitive force control.

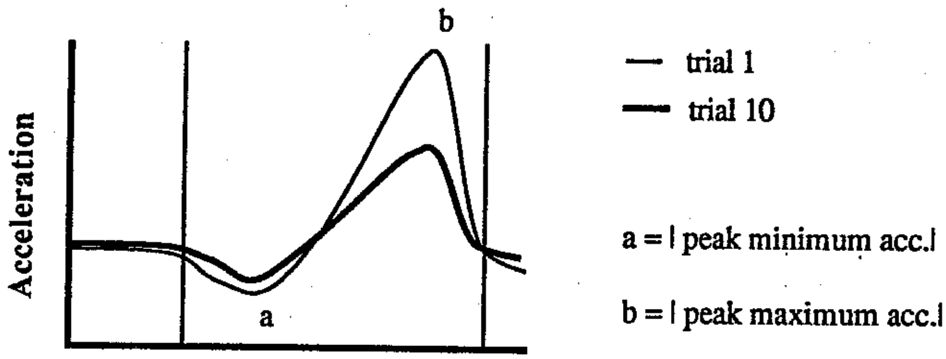
amplitude of the acceleration–time curve across the different impact force requirements of trials 1–10 were examined in three ways. First, the value of the peak positive and peak negative accelerations in the Z axis were determined and subjected to independent 3–way (skill level x task condition x impact force requirement) ANOVAs. Second, correlation co–efficients were computed between trial number, peak positive and peak negative Z accelerations and these co–efficients analysed using a skill level x task condition x swing direction (positive = downswing; negative = backswing) ANOVA. The correlation between trial number and peak positive acceleration was used as an indicator of downswing control of impact force and the correlation between trial number and peak negative acceleration an indication of impact force control through modulation of force during the backswing. The relative strengths of these two correlations provided an indication of the likely locus of impact force control. Third, the possibility that the force curve might be proportionally amplified (or de–amplified) for different impact force requirements was examined by subjecting the correlations between the peak positive and peak negative accelerations to a group x condition ANOVA. A more rigorous test of the same proportional force model was made by calculating the ratio of peak positive acceleration to the sum of the absolute value of peak positive and negative acceleration. This ratio was then regressed against the peak positive plus negative acceleration sum for each trial for each individual subject with the expectation of a zero slope for subjects using a proportional scaling strategy (Figure 6a). The actual regression slopes were tested against 0 and the number of subjects within each group violating the proportional acceleration (force) model were tabulated.

Possible changes in the temporal dimension of the Z acceleration patterns were assessed in three ways, mirroring the analyses done on the force (acceleration) dimension. First, the durations of the backswing and forward swing of the cue, as determined from the velocity–time curve, were submitted to three–way ANOVAs using the same factors as per the peak acceleration analyses. Second, correlations between trial number and backswing and downswing durations were computed and subjected to a group x condition x swing component ANOVA. Third, the possible temporal scaling of the backswing and downswing movement times (i.e., the possibility that the whole pattern is proportionally sped up or slowed down in time to accommodate the altered impact force demands) was assessed by using both backswing and downswing duration correlations and the constant proportion test of Gentner (1987); a modification of which has been described above for testing potential force (acceleration) scalings. For each individual subject backswing duration was determined as a proportion of the total movement time (from SOM to impact) and then this proportion regressed against total movement time (Figure 6b). Significant differences between the observed slope and the slope of 0 needed to support a temporal proportionality model were assessed for both task conditions for each subject and the number of violations of the model was tabulated for each skill group. According to Gentner (1987), the temporal proportionality model should be rejected if more than 10% of the subjects show slopes differing significantly from 0.

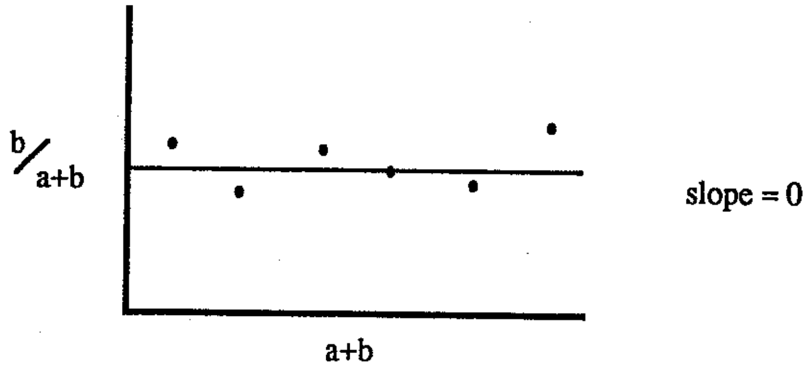
Results and Discussion

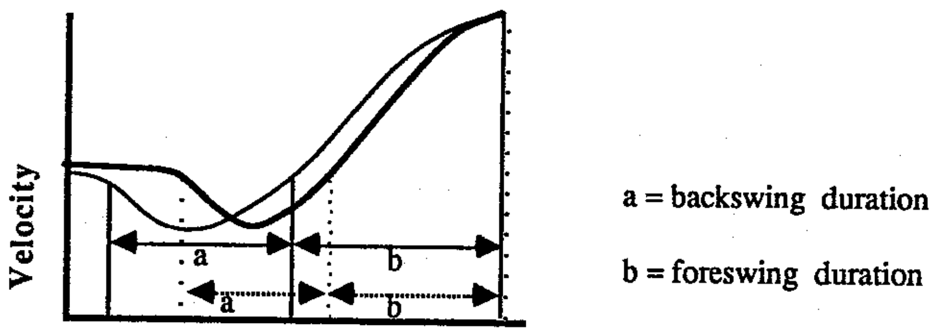
Constant Force Conditions

Impact velocity measures Figures 7–9 plot impact velocity in the Z, X, and Y axes as a function of the skill level of the subjects and the task condition (whether it is the

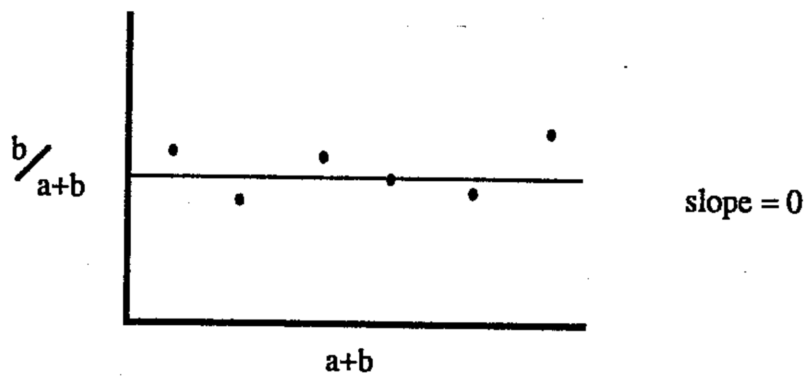


if <u>relative force</u> is proportionally scaled expect:





if <u>relative timing</u> is proportionally scaled expect:



<u>Figure 6</u>: Methods for examining if (a) proportionate relative force and (b) proportionate relative timing hold within the cue kinematics.

cue ball or the object ball which has to be positioned).

Analysis of the velocity of the cue at impact in the desired direction down the line of the table (the Z axis) reveals a significant skill level x task condition interaction ($F(2,23)=8.524, p<0.001$). Simple main effects analysis reveals that this interaction is due to significantly greater cue velocities at impact under the condition where the object ball rather than the cue ball has to be positioned for the expert subjects ($F(1,4)=7.721, p<0.05$) but not for the novice subjects ($F(1,13)=2.613, p>0.05$). As the nature of the task dictates that the object ball condition necessitates a higher cue velocity at impact than the cue ball condition if the same finishing position is to be achieved, it is clear that the response of the expert and intermediate group reflects an adaptive force output increase for the object ball condition whereas the novices fail to make these task-essential adaptations.

Cue velocity at impact in the X axis (across the table) should ideally be zero in the current task set-up to ensure that the cue ball is hit in a direct line up the table and none of the desired forward impulse is dissipated laterally. Analysis of the X impact velocity reveals no significant group ($F(2,24)=1.306, p>0.05$) or group x condition ($F(2,24)=1.837, p>0.05$) effects although the mean trend is in the expected direction of higher horizontal impact velocity for the novice subjects (Figure 8).

As is the case with medio-lateral impact velocity, vertical (Y-axis) impact velocity should also approach zero in the ideal orthodox shot. Although in some cases vertical cue velocity at impact may be needed to apply restraining ("stun") spin to the cue ball in the current task configuration the closer the cue is to parallel with the table, and hence the

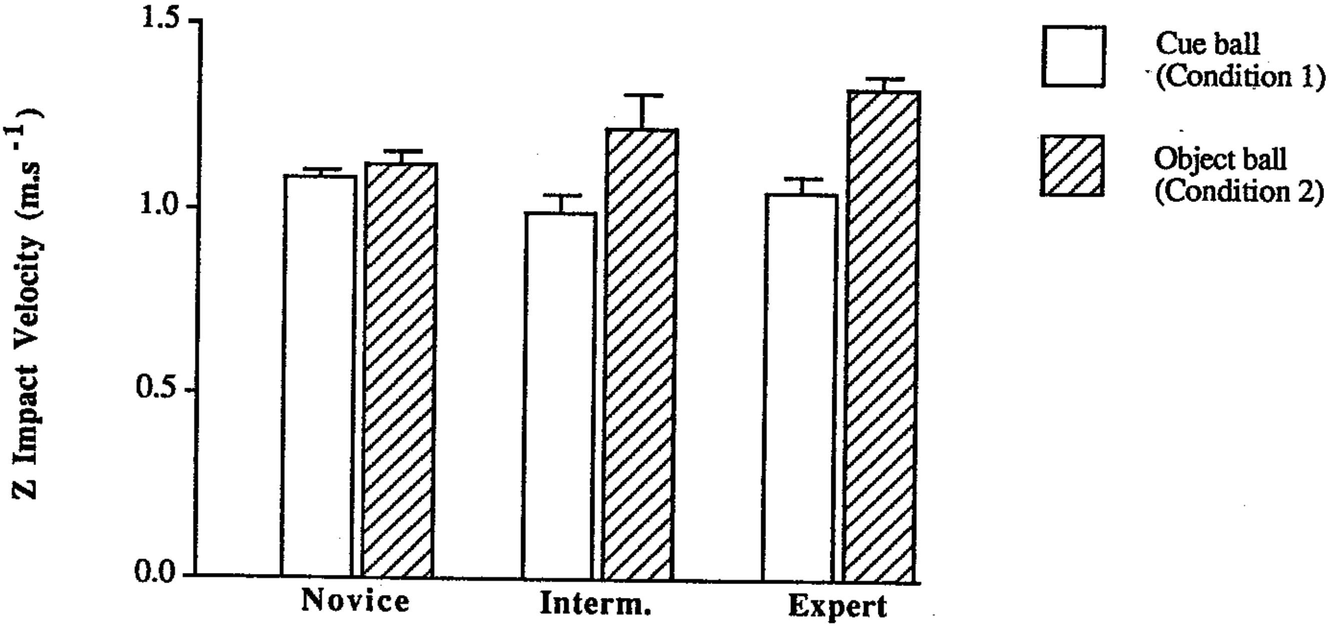


Figure 7: Mean Z impact velocity (and standard error) as a function of skill level and condition.

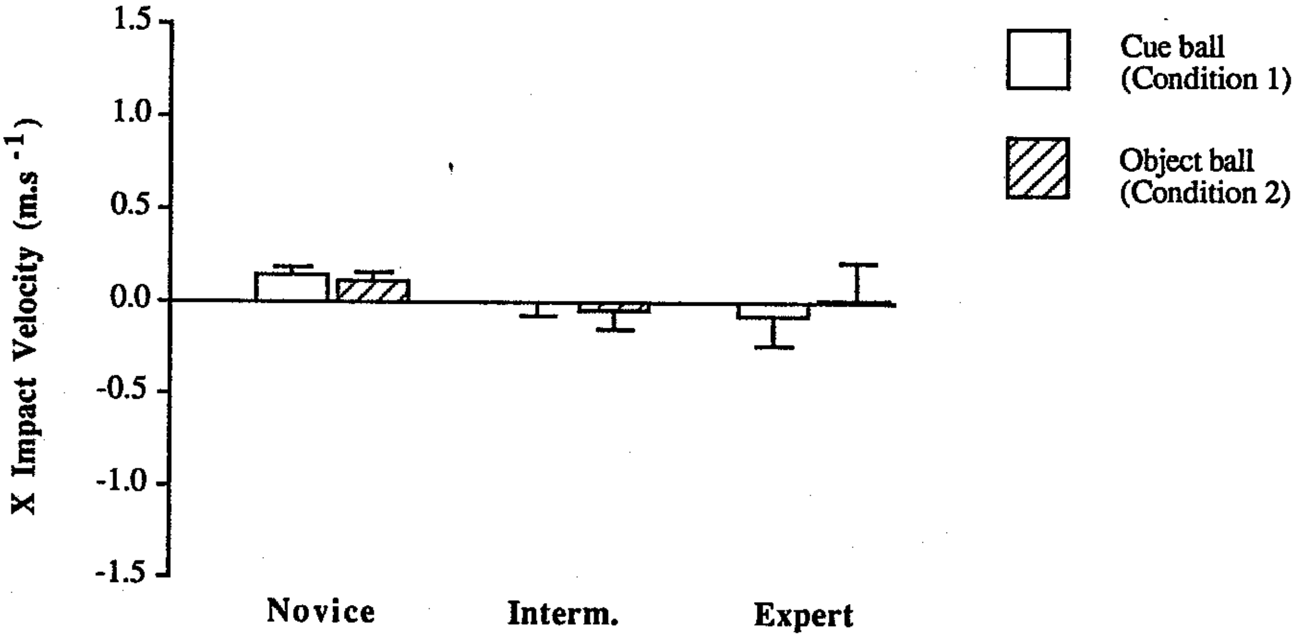


Figure 8: Mean X impact velocity (and standard error) as a function of skill level and condition.

lower the vertical velocity component at impact, the more mechanically efficient the shot execution will be. A significant group main effect ($F(2,23)=8.448, p<0.01$) was observed on this measure due to significantly lower vertical impact velocity for the expert subjects compared to the novice subjects ($p<0.05$)(Figure 9). The intermediate skill level subjects assume intermediate values on this measure, not differing significantly from either the expert or novice group. The expert–novice difference in vertical impact velocity persisted across both the cue ball and object ball conditions, there being no condition ($F(1,23)=2.159, p>0.05$) nor higher order group x condition interaction ($F(2,23) = 0.127$, $p>0.05$) on this measure. These analyses suggest that as skill is acquired in billiards and snooker subjects acquire a movement pattern which places the line of force nearly directly through the centre of the cue ball, minimising the inefficient application of cue forces in the vertical plane. Of course deviations from this line of force application will be necessary in some situations where either "stun" or side–spin needs to be applied to the cue ball in order to position it ideally for the next shot.

Velocity–time profile measures The respective CVs for the different skill groups under the different task conditions are displayed in Figure 10 (for the Z axis), Figure 11 (for the X axis) and Figure 12 (for the Y axis). In all cases the lower the CV measure the higher the trial–to–trial consistency the subject produces in the motion of the cue.

A significant skill group main effect exists with respect to velocity in the longitudinal (Z) axis ($F(2,24)=4.073, p<0.05$) with a significantly lower CV for the expert group compared to the novice group ($p<0.05$). The intermediate CV of the intermediate skill group argues further for longitudinal velocity pattern consistency as a strong correlate

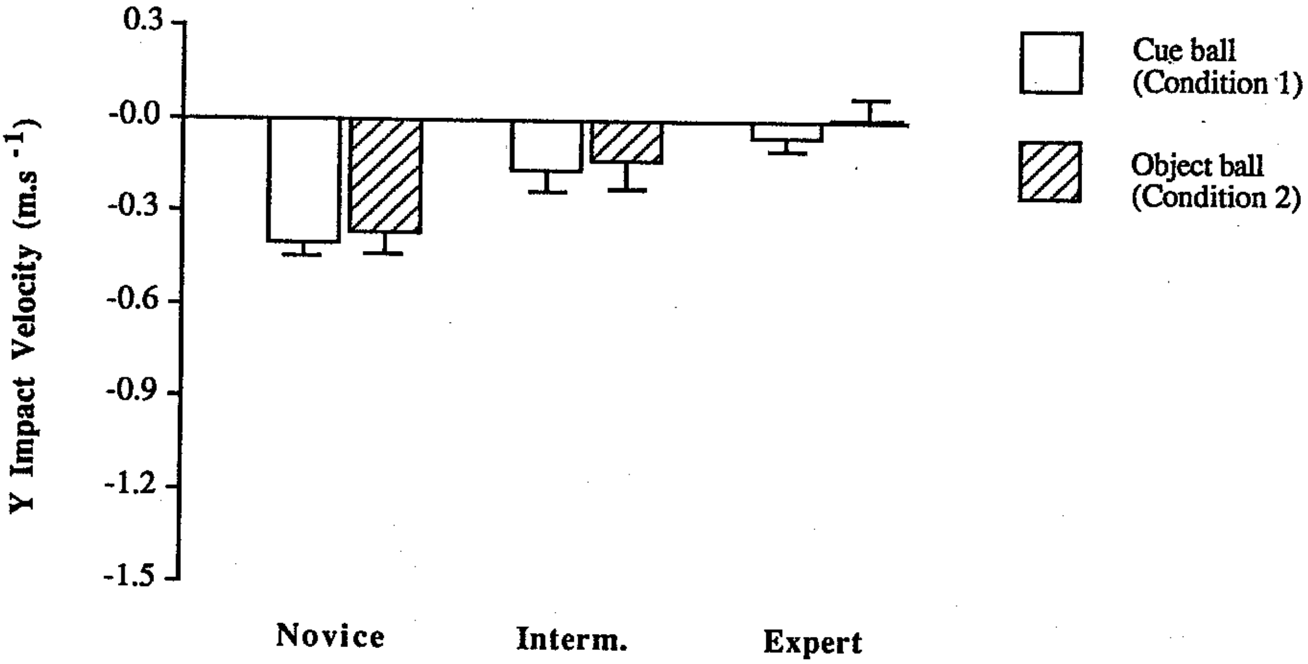


Figure 9: Mean Y impact velocity (and standard error) as a function of skill level and condition.

of skill development. A significant condition main effect is also apparent for this measure ($F(1,24)=4.489$, $p<0.05$) due to greater variability under the object ball condition than under the cue ball condition. One interpretation of this finding is that variability simply increases linearly in response to the absolute force that needs to be generated – an observation consistent with findings from a number of laboratory tasks (Schmidt, Zelaznik, & Frank, 1978; Sherwood & Schmidt, 1980). An alternative, perhaps more interesting, interpretation is that it is the addition of an extra task demand in the object ball condition (the necessity to play the cue ball into the object ball) that disturbs the consistency of the cue kinematics, providing an objective demonstration of the effects of distraction on motor control. Such effects form the basis of much of the existing practice in sport psychology but objective demonstrations of movement pattern disturbances of this type are surprisingly rare in the literature. In support of the latter interpretation the pattern variability increases quite markedly for only relativley minor increases in the force output requirements of the object ball condition. Skill level does not interact significantly with the extent of cue ball–to–object ball CV changes ($F(2,24)=1.537$, $p>0.05$) although the trends are in the predicted direction i.e., the mean CV increases from condition 1 to condition 2 are greatest for the novice group and least for the expert group (Figure 10).

Variability in the medio–lateral velocity patterns do not differ significantly between the skill groups ($F(2,24)=1.479, p>0.05$) or between the task conditions ($F(1,24)=0.249, p>0.05$) although the mean trends for the skill group comparison are in the expected direction of lower CVs for experts than novices (Figure 11). A power test applied to the skill level data revealed that sample sizes of as little as 20 per group may be sufficient to make the skill level effect statistically significant.

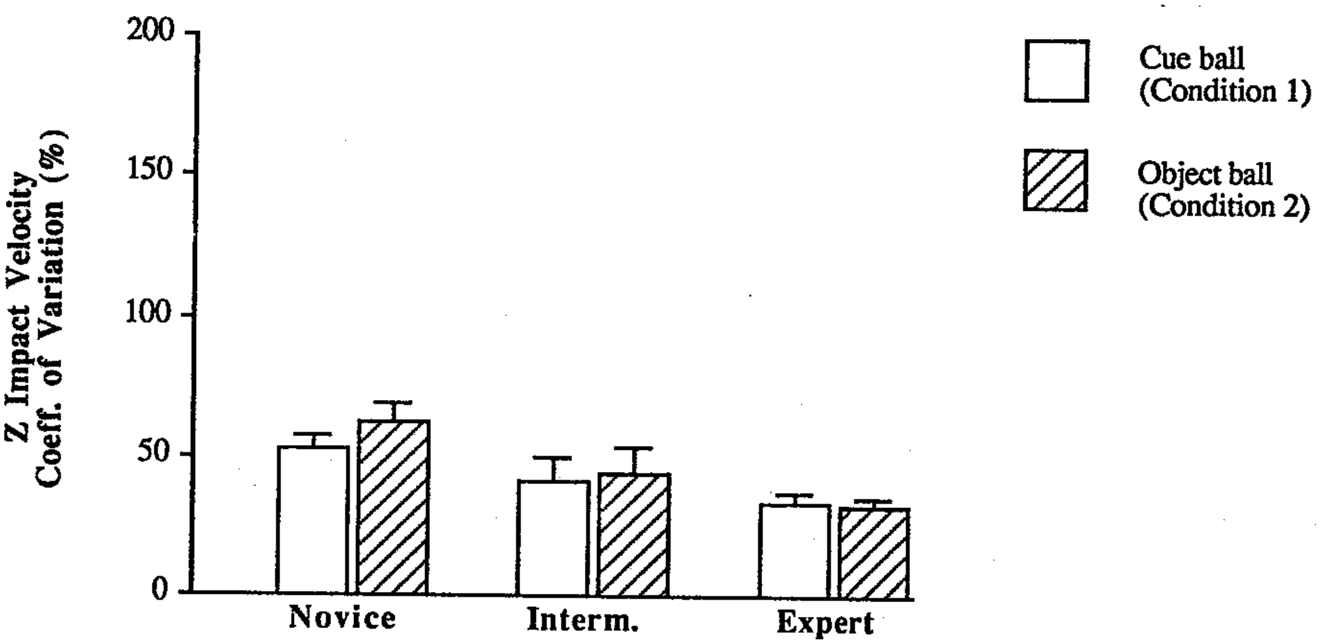


Figure 10: Mean Z impact velocity co–efficient of variation (and standard error) as a function of skill level and condition.

The analyses of the CV of the vertical (Y axis) velocity patterns revealed essentially the same conclusions as for the analysis of the medio-lateral velocity pattern. Both group ($F(2,24)=0.056, p>0.05$) and condition ($F(1,24)=0.771, p>0.05$) main effects were not statistically significant and there was no interaction between the two factors ($F(2,24)=0.603, p>0.05$). The trend in the group data was for lower CVs for the expert group (see Figure 12), although in this case the power test indicated that improbable group sizes (of the order of 500/group) would be needed for this effect to be statistically significant.

In summary, the analyses of the subjects' performances on the tasks requiring constant force output for success reinforce the view that the superior task performance of the expert players is a direct result of their greater trial-to-trial cue pattern consistency. The experts' performance differs from that of the novices in showing a greater proximity to the idealized mechanical performance model for the task (i.e., highly consistent Z axis velocity and essentially zero level X and Y axis velocities) and in showing adaptive adjustments of longitudinal impact velocities to accommodate the altered task demands from the cue ball to the object ball condition. Consistent with the anecdotes of experienced billiards and snooker players and coaches (e.g., Karnehm, 1976) the addition of the object ball to the task has a powerful detrimental effect on cue pattern consistency for players of all levels of skill although the trend is for this disturbance to be most pronounced in novice players and least pronounced in expert players.

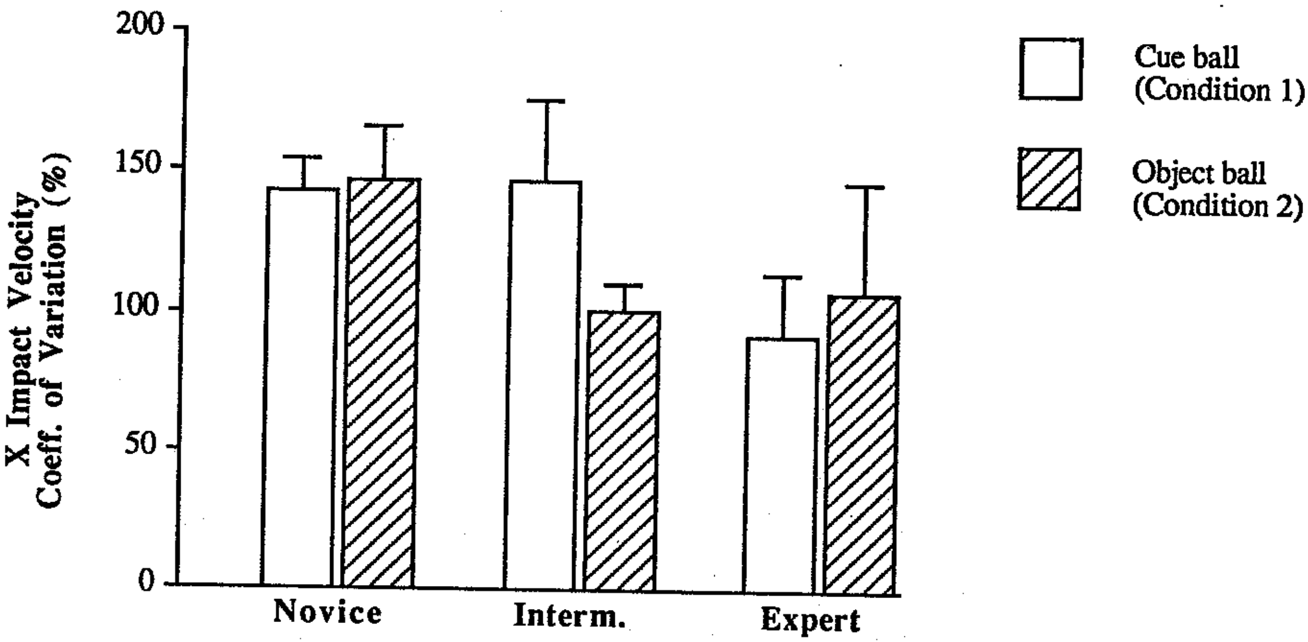


Figure 11: Mean X impact velocity co-efficient of variation (and standard error) as a function of skill level and condition.

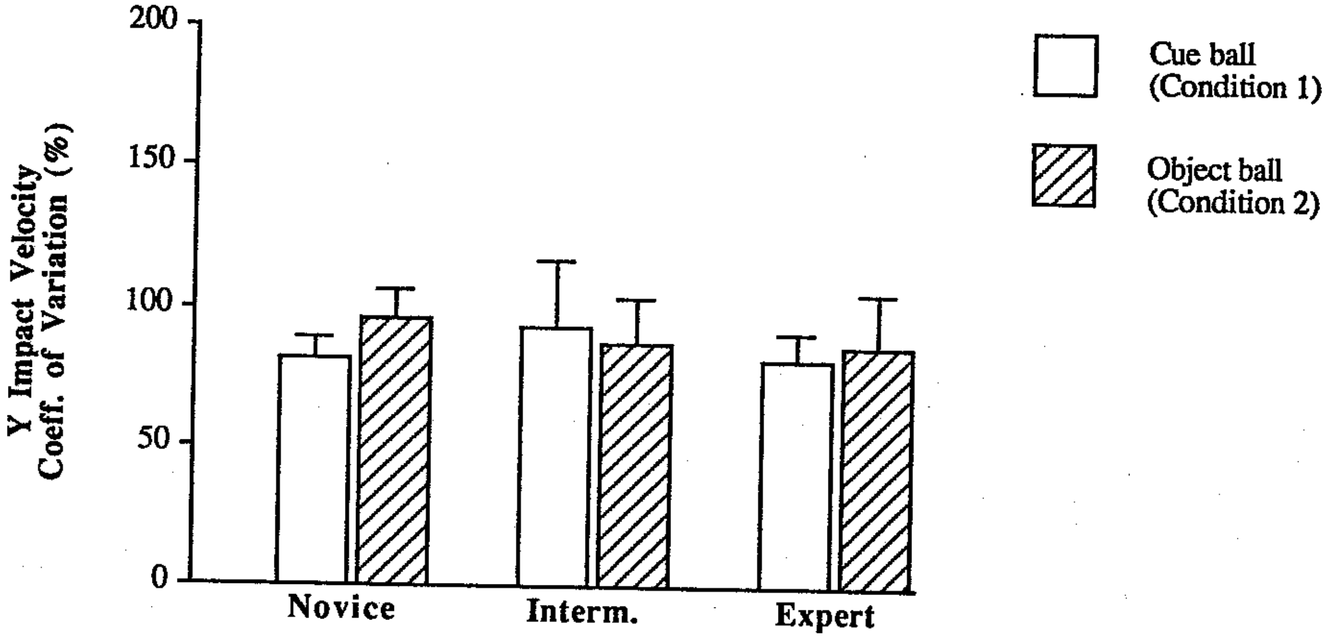


Figure 12: Mean Y impact velocity co-efficient of variation (and standard error) as a function of skill level and condition.

Variable Force Conditions

The variable force tasks require the subjects to be able to control the impulse applied to the cue ball during impact, and this in turn requires that the momentum of the cue be controlled. As the cue is in contact with the cue ball for only a very short period of time the only variable likely to be under the control of the subject in this task is impact force. Given the unchanging mass of the cue-arm system active response to the task demands in this second phase of the study should be reflected in modulations of the impact acceleration of the cue in the Z-dimension in direct proportion to the desired finishing position of either the cue or object ball. Impact velocity measures in the Z axis were first analyzed to determine if the cue kinematics at impact were indeed modulated to meet the changing task demands and if the skill groups varied in their modulation sensitivity. Subsequent analyses were directed at the complete Z axial acceleration-time (and velocity-time) pattern from SOM to impact in an attempt to ascertain how any impact force modulations were generated.

Impact velocity measures Impact cue velocity in the longitudinal axis varied significantly in the variable force conditions as a function of the force demands of the task (given by the clustering of trials into 'hard', 'medium' and 'soft' impact requirements) ($F(2,46)=15.323, p<0.001$), but the extent of impact cue velocity changes across the different trial groupings did not vary between the expert, intermediate and novice players ($F(4,46)=1.698, p>0.05$). Impact velocity of the cue was significantly ($p<0.05$) reduced from the trials requiring 'hard' impact (trials 1-3) to those requiring 'medium' impact (trials 4-7) and again from the 'medium' impact to the 'soft' impact trials (trials 8-10) (Figure 13). All subjects therefore displayed a capability to modulate cue velocity at impact in a way which satisfied the altered task demands, although, perhaps surprisingly, experts appeared no better at this force modulation than novices.

This conclusion with respect to group equivalence in impact force control was supported by the more sensitive analysis of the correlations between impact force and trial number. A correlational value of −1.00 was to be expected if perfect force modulation was being enacted (cf. Figure 5).

Acceleration- and velocity-time profile measures It is apparent from the preceding analyses that all subjects were able to adaptively modulate the velocity of the cue at impact although this control was far from perfect. What was not apparent from the impact analyses was how this modulation was achieved and how the force-time profile was altered on each trial in order to adjust the cue's impact velocity. The analyses that follow attempt to shed some light on how the force-time curves (from SOM to impact) were modified to accommodate the variable force requirements of the task by sequentially examining the responses of peak positive and peak negative acceleration (as an indicator of backswing and downswing force, respectively) and backswing and downswing movement duration to the trial-to-trial variations in required impact force. At least two simple control strategies appeared possible with respect to control of the force dimensions viz., (1) downswing force (as shown by peak forward acceleration) but not backswing force (as shown by peak negative acceleration) may be scaled directly to desired impact force or (2) the force component might be scaled throughout the whole movement by proportionally scaling both the backswing and downswing forces. Likewise, with respect to the temporal dimension of the force-time curve, (1) the time course of the backswing and downswing phases may be independently altered in response to the impact force

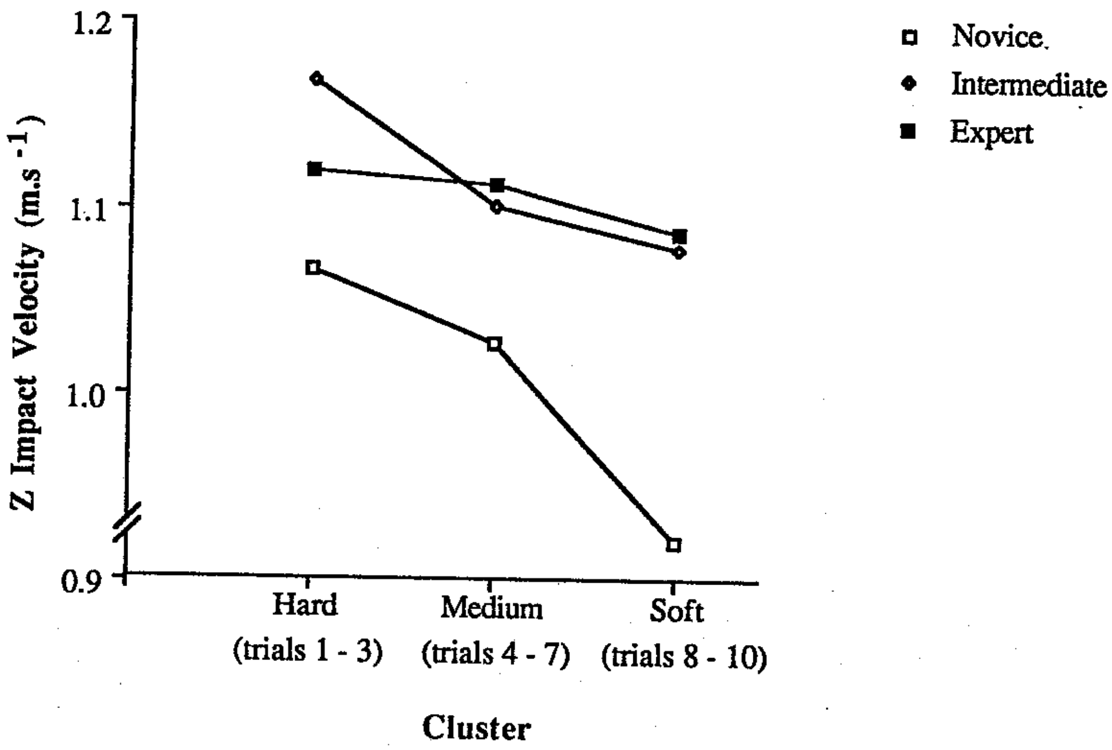


Figure 13: Z impact velocity as a function of skill level and trial clusters in the variable force task.

demands or (2) the time course of both the backswing and downswing phases of the movement may be proportionally scaled. An attempt was made to discriminate between the use of these and other possible control strategies and to assess any possible skill-related differences in strategy selection.

Analysis of peak negative acceleration (i.e., maximum acceleration during the backswing) revealed a significant effect due to the trial clusters ($F(2,46)=10.032, p<0.001$), with significantly greater peak acceleration in the backswing for the 'hard' impact trials (trials 1–3) than either the 'medium' (trials 4–7) or 'soft' trials (trials 8–10) (Figure 14). This effect was not mediated by the skill level of the subjects ($F(4,46)=0.773, p>0.05$). The corresponding analyses of peak positive acceleration (i.e., maximum acceleration during the forward swing of the cue) revealed essentially identical statistical conclusions. A significantly higher peak positive acceleration was found for the 'hard' impact trial cluster than for either the 'medium' or 'soft' impact clusters ($F(2,46)=20.324, p<0.001$) with this observation being independent of the skill level of the subjects ($F(4,46)=1.162, p>0.05$) (Figure 15). Collectively these two analyses provided some evidence that both downswing and backswing force production were modulated in response to the impact force demands but that this modulation was not uniform across the whole range of impact force requirements. Greater adjustments in force maxima away from that used for 'medium' force shots were made in both the backward and forward directions for the 'hard' impact shots than for the 'soft' shots.

Significantly higher correlations existed between peak positive acceleration and trial number ($r=0.51$) than between peak negative acceleration and trial number ($r=0.38$)

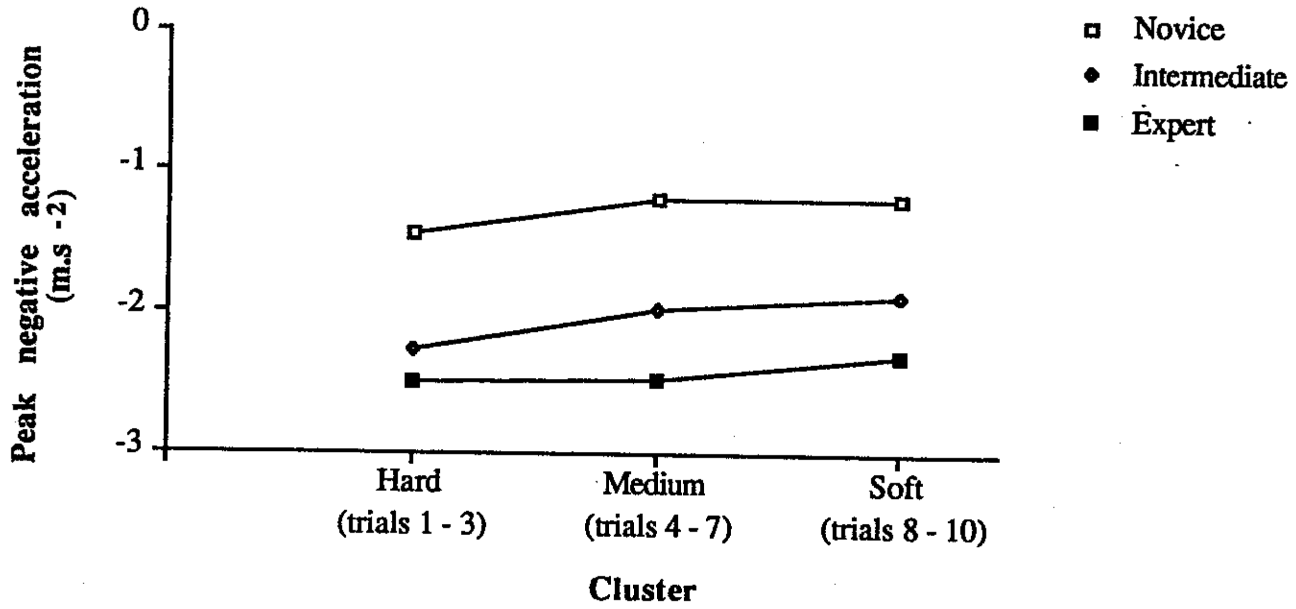


Figure 14: Peak negative acceleration as a function of skill level and trial clusters in the variable force task.

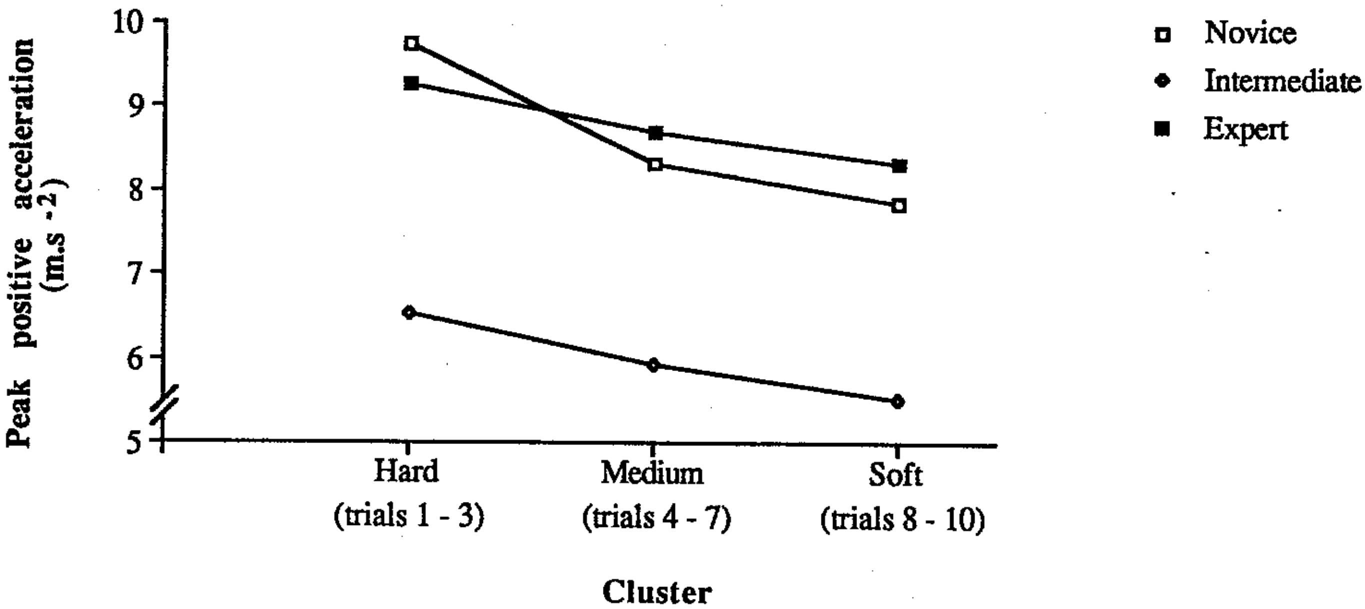


Figure 15: Peak positive acceleration as a function of skill level and trial clusters in the variable force task.

($F(1,22)=8.375, p<0.01$) indicating that it was more peak force in the downswing of the cue than in the backswing which was sensitively controlled to produce the desired trial-to-trial variations in impact force. This same control strategy appeared true for players of all skill levels, there being no significant group x swing direction interaction in the correlation magnitudes ($F(2,22)=0.613, p>0.05$).

Correlations between the absolute magnitudes of peak acceleration during the backswing and forward phases were only moderate (ranging from $r=0.32$ for the expert group to $r=0.58$ for the novice group), arguing against control of the whole movement by a motor program with relative force as an invariant parameter (cf. Schmidt, 1985; Hollerbach, 1978). There were no significant group differences in the magnitude of the backswing-forward swing peak acceleration correlations ($F(2,22)=1.835, p>0.05$) nor were there any apparent in the regressional analyses. Rejection of a proportional force model of control was also supported by the analyses of the slope of the regressions calculated for each subject between relative peak positive acceleration and absolute (positive and negative) peak acceleration (cf. Figure 6a). More than 10% of the individual subjects showed regression slopes differing significantly from 0 under both the cue ball and the object ball conditions (cf. Gentner, 1987).

Some, but not all, components of the temporal dimension of the acceleration- and velocity-time curves appeared to be modified to meet the differing trial-to-trial impact force requirements of the second phase of the study. The duration of the backswing phase of the cue movement varied systematically between the different trial clusters ($F(2,44)=3.318, p<0.05$), there being a significantly longer backswing duration for the trials requiring 'hard' impact than those requiring 'soft' impact. This effect was not mediated by the level of expertise of the subjects ($F(4,44)=0.930, p>0.05$) (Figure 16). Although experts had, on average across all trials, slightly shorter backswing durations ($\bar{x}$=475ms) than the intermediates ($\bar{x}$=508ms) and novices ($\bar{x}$=510ms) this effect did not reach statistical significance ($F(2,22)=0.072, p>0.05$). Novices were clearly more variable in their backswing duration than either the intermediate or expert players, in both absolute and relative terms, (see standard error plots within Figure 16), a situation opposite to that observed in skills where a moving rather than a stationary object must be struck (cf. Burgess-Limerick, Abernethy, & Neal, in press).

Unlike the duration of the backswing of the cue, the duration of the forward swing of the cue did not change significantly from the 'hard' impact cluster to the 'soft' ($F(2,44)=2.883, p>0.05$), although the trend was for shorter downswing durations for the more forceful shots (x 'hard'=293ms; $\bar{x}$ 'soft'=311ms). Across all trials the intermediate skill group had longer downswing durations ($\bar{x}$=499ms) than either the expert ($\bar{x}$=269) or novice ($\bar{x}$=214) group ($F(2,22)=15.429, p<0.001$). A more interesting trend, albeit a non-significant one ($F(4,44)=0.390, p>0.05$), was for downswing duration to be less variable across the different trial clusters for the expert group than for the other groups. Only a 6 ms difference separated the mean downswing durations of the 'hard', 'medium' and 'soft' trial clusters for the expert group, compared with a 21ms range for the intermediate group and a 20ms range for the novice group (Figure 17). The control tendency for all skill groups was toward keeping downswing movement time constant and varying backswing duration – a control strategy advanced previously in the literature as the operational timing hypothesis (Tyldesley & Whiting, 1975; Wollstein & Abernethy, 1988).

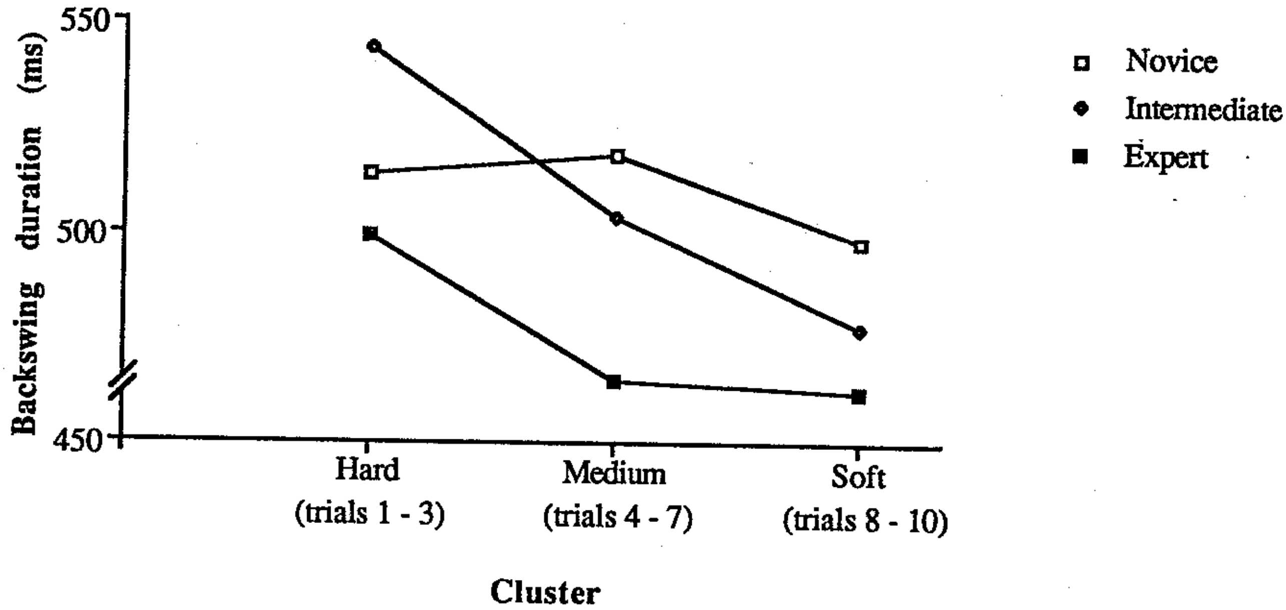


Figure 16: Backswing duration as a function of skill level and trial clusters in the variable force task.

Correlations between the impact force requirements of the task (as given by trial number) and the backswing and downswing movement time durations were generally of very low order. Although the backswing duration and the downswing duration differed significantly in their correlation with trial number ($F(1,23)=12.348, p<0.01$), the mean correlations of −0.135 and 0.134 respectively were of trivial magnitude, accounting for less than 2% of the variance. The correlations were low for all skill groups (ranging from −0.238 to 0.231) and there was no significant group differences in either the backswing or downswing correlations ($F(2,23)=0.888, p>0.05$). Comparison of the magnitudes of the correlations between trial number and peak positive and peak negative acceleration indicated that impact force was controlled primarily by altering the peak force applied to the cue during the forward swing rather than by altering the temporal duration of either the backswing or forward swing of the cue. For the more forceful shots the cue was taken back further (resulting in a longer backswing duration) and faster (resulting in higher acceleration amplitudes) but the principal control was exerted through increasing peak force in the forward swing without altering the movement duration. The same form of control appeared to be exerted by expert, intermediate and novice performers.

Backswing and forward swing durations are poorly correlated for all three skill groups ($r_{experts} = -0.246$; $r_{intermediates} = -0.326$; $r_{novices} = -0.231$), indicating a lack of temporal proportionality across the whole cue movement. A more detailed scrutiny of the possible control of the cue movement through the preservation of invariant relative timing conducted through the application of Gentner's (1982) constant proportion test (see Figure 6b) supported a similar conclusion. For the cue ball condition, 2 of 6 experts, 2 of 7

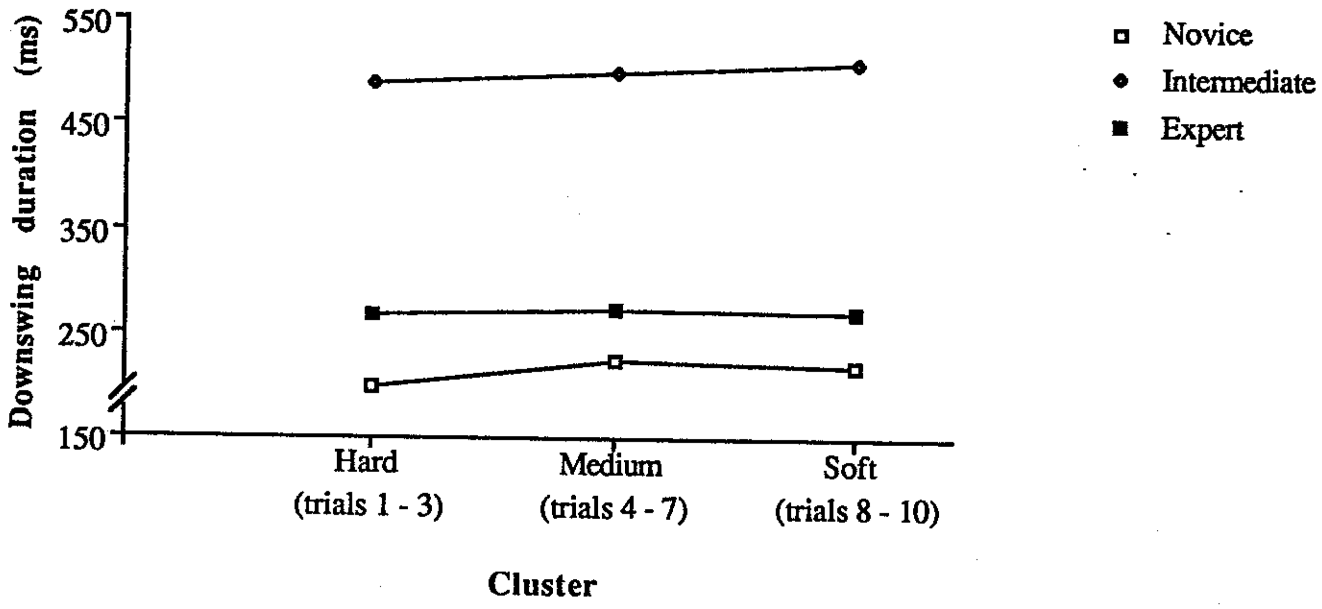


Figure 17: Downswing duration as a function of skill level and trial clusters in the variable force task.

intermediates and 4 of 15 novices had regression slopes differing significantly from 0 whereas for the object ball condition the corresponding number of expert, intermediate and novice subjects violating the temporal proportionality model were 6, 1 and 2 respectively. These data, while consistent with recent analyses of other motor skills (Burgess–Limerick, Neal & Abernethy, in press; Wann & Nimmo–Smith, 1990), are evidence against the use of a control strategy in which relative timing is preserved as an invariant feature (e.g., Schmidt, 1985,1988). Backswing and forward swing cue durations are no more likely to be proportionally scaled for experts than they are for novices.

Conclusions

In this study experts were more clearly discriminated from novices on the constant force task conditions than on the variable force tasks emphasizing closed rather than open skill attributes as the principal correlate of skill level. In the constant force tasks experts showed greater trial–to–trial consistency in the cue kinematics and produced kinematics which minimized non–essential lateral and vertical impulses with control restricted essentially to the crucial longitudinal force axis. Experts adapted better to the altered task demands of positioning an object ball rather than a cue ball than did novices and showed less kinematic disturbance with the presence of the object ball than did the other skill groups. The presence of some increased cue pattern variability with the introduction of the object ball for even the expert subjects implicated an important place for realistic distractors in the practice routines of players of all skill levels.

In the difficult variable force task, impact force was required to be systematically varied, rather than held constant, from trial to trial. The three skill groups did not differ in their ability to sensitively modulate impact force in direct proportion to the required finishing position of the cue or object ball suggesting that the task difficulty may have forced subjects to attempt to make adjustments verging on the limits of the difference limen for force production. The relatively poor performance of the experts on the variable force tasks suggests, given the apparent importance of precise force modulation in game situations, that practice under conditions similar to the experimental conditions created in this study may be worthy of consideration as a training procedure. All groups altered impact force primarily by controlling the peak acceleration amplitude of the cue during the forward swing rather than systematically altering, on a trial–to–trial basis, the temporal dimensions of the acceleration–time curve. No evidence was obtained, for any of the skill groups, of either peak force or swing duration being proportionally scaled from the backswing to the forward swing.

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Requests for reprints and any further correspondence related to this paper should be addressed to Bruce Abernethy, Department of Human Movement Studies, The University of Queensland, Australia, 4072. (Fax No. 61–7–3656877 or email ba@brolga.cc.uq.oz.au).

WHAT MAKES THE EXPERT SPORTS PERFORMER BETTER THAN THE NOVICE?

THE CASE OF BILLIARDS AND SNOOKER.

Bruce Abernethy, Robert J. Neal, Craig M. Engstrom
and Paul V. Koning

Department of Human Movement Studies
The University of Queensland, Australia

Running Head: Billiards & Snooker

INTRODUCTION

The sport of billiards and snooker appears to require players to couple together a unique combination of decision-making skills, visual aiming skills and unidirectional force control skills in order to perform well. Little however is known about these component skills, their relative importance in determining a player's performance limits, and their potential trainability. As Jack Karnehm (1976) has described in his widely-read text on coaching and playing in these sports, non-expert players

> '... when they come to the shot so critical for the continuation of a nice size break, they fail because they do not apply just the right amount of cue ball control, although they knew or felt it was within their power to do so'.

Further he suggests, in acknowledgment of the current dearth of scientifically based knowledge on billiards and snooker performance, that

> '... the reasons that cause this (the commitment of critical errors) to occur so consistently belong to a phase of the game not usually studied or understood and having nothing to do with ambition or experience ... it is the mental and physical approach to the shot'.

In this paper we briefly report on the findings of a research project funded by the Australian Sports Commission's Applied Sports Research Programme in which the nature of expertise in billiards and snooker was examined. Detailed descriptions of the technical elements of the project are available in two companion reports (Abernethy, Neal, & Koning, 1991; Neal, Abernethy, & Engstrom, 1991).

The project proceeded in four steps by:

1. determining the component stages involved in successful task performance;

2. devising tests to separately measure elements of performance within each of the component stages;
3. comparing the performance of expert, intermediate and novice players on each of the devised tests; and
4. drawing implications from the expert–novice comparisons as to the limiting factors to skilled performance in this sport and to some potential directions for enhancing the rate of skill acquisition in this sport.

The subjects in this study were seven expert players, ranked within the top 30 in Australia, seven intermediate (club–level) players and 15 novice players (all of whom had less than one year of playing experience).

COMPONENT STAGES IN PERFORMANCE: SHOT SELECTION, PREPARATION AND EXECUTION

There would appear to be, as Table 1 illustrates, at least three stages involved in a successful single trial performance in billiards and snooker. Successful single trial performance involves not only potting the desired object ball into a nominated pocket but also returning the cue ball to the optimal table location for the simplest possible execution of the next shot.

The first stage of performance, which depends largely on the combined cognitive and visual–perceptual skills of the player, involves deciding what shot option (and, in most cases, series of shot options) to select from the range of options which are available on the table. In selecting the most desirable option the player needs to consider not only

Table 1: Component processes, limiting factors and measureable elements of billiards and snooker performance

COMPONENT PROCESSES	SHOT–SELECTION	SHOT–PREPARATION	SHOT–EXECUTION
	•Deciding what shot option or series of shots to select •Shot selection includes consideration of optimal finishing position of the cue ball for the next shot	•Visual alignment of the cue, and desired contact points on the cue and object ball	•Application of desired force through the cue to the cue ball at the required point and direction of impact
LIMITING FACTORS	Cognition & Visual–Perception	Visual–Perception	Motor Control
MEASURABLE ELEMENTS	• Pattern recall • Pattern recognition • Breadth & depth of planning • Situation evaluation	• Visual acuity • Depth perception & stereopsis • Ocular muscle balance • Colour vision • Hand–eye dominance	• Force consistency control • Force modulation control

the shot difficulty with respect to his/her skill level, but also the unfolding series of shots (i.e., the potential 'break') which, in turn, dictate the required finishing position of the cue ball after each shot. All of this planning and shot-selection decision-making must be made within the context of the current score and the available points left on the table. The player's ability to recognize and recall structured patterns within the distribution of balls on the table, the speed of their decision-making, breadth and depth of their planning of shots in advance of the current shot and their ability to accurately evaluate the relative strength of given game positions and scenarios are all measurable elements of a player's capability to handle the demands of this stage of the billiards and snooker task.

The second identifiable stage of billiards and snooker performance involves the set-up for the shot and, in particular, the visual alignment of the forward path of the cue with the desired contact point on the cue ball and the desired impact point on the object ball. Performance in this stage of the task is clearly dependent upon the individual player's basic visual skills. For this reason, standard optometric measures of acuity, depth perception, ocular muscle balance, ocular dominance and colour vision provide useful tests of elements of this stage of performance (see again Table 1).

The final, most obvious, stage of performance involves actual shot execution with the motor control capabilities of the player acting as a limiting factor at this stage of performance. Measurements of the acceleration characteristics of the cue in tasks in which the player's are required to either reproduce exactly the force applied in a previous shot or deliberately increase or decrease the force application slightly from the preceding shot provide an avenue to assess both the consistency and adaptability of each player's motor control.

TESTS RELATED TO SHOT SELECTION AND WHAT THEY REVEALED

Tests of Pattern Recall The purpose of the pattern recall test was to determine the respective capabilities of the expert, intermediate and novice players to rapidly encode the pattern or structure of the balls on the table. The test used was a modification of that used earlier in studies of expertise in chess (e.g., de Groot, 1965) and fast ball sports (e.g., Allard, Graham, & Paarsalu, 1980). Subjects were shown, for a period of 5 seconds, slides which depicted the arrangement of balls on the table under (a) normal game conditions with all the colours present, (b) normal game conditions but with all balls being of uniform (red) colour and (c) atypical conditions in which all the normal colours were present but the balls were distributed randomly around the table, with the colours not placed on their normal spots. The subject's task, for each slide, was to record, in a booklet containing scaled representations of a billiards table, the position of each of the balls present in the slide. Analysis of the percentage of balls on the table correctly recalled indicated that the expert's advantage on this task was very situation-specific, existing only when the slides depicted displays containing structure with the coloured balls located in their normal (expected) positions. Moving the coloured balls from their normal locations (the unstructured condition) removed the expert player's pattern recall superiority. These findings indicate that expert players are able to pick-up the 'game pattern' more effectively than novice players and this, in turn, may help explain their apparent ability to 'see' and predict in advance potential breaks better than lesser skilled players.

Tests of Pattern Recognition To determine if expert players memorize more information than lesser skilled players about patterns of play they have previously experienced and then use this information to guide shot selection in future games, a pattern recognition test was administered similar to that used previously with board games players (Charness, 1979; Goldin, 1978). The subjects were shown a total of 28 slides, half of which they had seen previously and half of which were new. The subject's task was to decide whether they had seen the slide before or not and to rate their confidence in their judgment. The expert players were found to have a superior ability to recognize previously encountered patterns than the lesser skilled players and this superior task performance was also mirrored by higher confidence in their own recognition judgments. When faced with given shot selection decisions expert and novice players clearly do not take in the same information; the experts have a more vast memory of stored patterns from previous game experiences, are able to perform a deeper level of analysis on the available pattern information, and are hence likely to be able to plan ahead more effectively than lesser skilled players lacking in this experiential base.

Tests of Forward Planning To examine the cognitive processes involved in making shot selection decisions the subjects were shown a videotape of a competition match between two of the world's leading professional players (Steve Davis & Mike Hallett). The videotaped game was stopped at various pivotal points in the match where the players were confronted with a large number of potential shot options and the subjects were required to think-aloud as to which shot or series of shots they would opt to play if they were in the position of the player on the videotaped match. Formal instructions, modified from Wagner and Scurrah's (1971) study of chess players, were given to all subjects and measures were taken of the time to commence verbalization, the number of shot options considered (as an indicator of breadth of planning), and the mean and maximum number of shots planned in advance (as indicators of depth of planning). The expert players were found to undertake greater depth of planning than the novices, planning on average 6 shots in advance of the current one compared with 4 shots by the novices. The expert players did not differ from the lesser skilled on the time taken to commence verbalizing their cognitions or on the breadth of planning undertaken.

Test of Situation Evaluation The purpose of this test was to measure the players' abilities to evaluate given game positions and to discriminate, with precision, differences in the advantages/disadvantages provided by given situations. The subjects were shown slides depicting the position of the balls on the table during representative early, middle and late game situations and were asked to rate how advantageous the situation would be if they were to play the next shot and (a) the scores were equal, (b) they were 10 points ahead or (c) they were 10 points behind. The task was based on one used previously in studying chess players by Holding (1979). The expert players were found, on average, to rate all situations as being more advantageous than did novices, perhaps simply reflecting a greater confidence in their own performance capabilities. A more important observation was the greater spread of ratings made by the expert players indicating superior evaluative discriminability. The current game score exerted a large influence on the evaluations made by novices whereas the skilled players gave evaluations which were more logical in terms of the points remaining on the table. The expert's evaluations were therefore largely prospectively–influenced (i.e., forward–thinking) whereas the novices's evaluations were largely retrospectively–influenced (i.e., dwelling on past events).

TESTS RELATED TO SHOT PREPARATION AND WHAT THEY REVEALED

The tests administered to tap performance in this second stage were all directed at assessing the visual sighting/alignment capabilities of the players.

Tests of Visual Acuity Static visual acuity was measured on the players as a clear focus on target points on the cue ball and the object ball may be necessary in order to achieve accurate 'straight–line' sighting. As the cue ball is typically located about arm's length from the eyes (approx. 1 m) while the target ball may be anything up to 4.5m away, the acuity measurements were made at both optically near (35 cm) and far (6 m) distances. No expert–novice differences were apparent for either binocular or monocular acuities measured at either the near or far distance with the mean values for both groups closely approximating the expected population norms. Billiards and snooker players of all skill levels did not appear to resolve visual detail any better or any worse than the general population.

Tests of Depth Perception The ability to perceive relative differences in object distance was assessed using the standard Howard–Dolman method. Depth perception ability might well be expected to set important limits on an individual player's judgment of not only shot distance but also of the required contact angle between the cue and object ball. The test was conducted over a 3.66 m distance, equivalent to the length of a full–size billiards table. Like the acuity measures, however, this standard optometric measure failed to discriminate between the expert and novice players in our sample. A follow–up test of stereopsis (the ability to discriminate differences in depth through the use of binocular vision), revealed values within the expected population norms for all the subjects in the study.

Tests of Ocular Muscle Balance Standard optometric phoria measures indicate the extent to which extraocular muscle balance occurs. Phorias are assessed by measuring the extent to which the axes of both eyes are in symmetry in viewing either near or far objects, with the assessment made independently for both the horizontal (lateral) and vertical planes. A reasonable expectation, given the apparent demands of the visual alignment stage of billiards and snooker performance, is that orthophoria (the case of perfect ocular muscle balance) or low levels of heterophoria (i.e., minimal deviations from orthophoria), in the horizontal plane in particular, may be essential for expert billiards and snooker performance. However, at both near and far test distances in both the horizontal and vertical planes, the phorias measured for the expert players were within the expected population norms and were essentially identical to those obtained for the novice and intermediate groups.

Tests of Colour Vision Adequate levels of colour vision are undoubtedly crucial for skilled performance in billiards and snooker given the importance which is assigned to the different colours. Standard Ishihara colour vision tests revealed, not surprisingly, an absence of colour vision defects in the expert and intermediate skill groups, although the same was also true for the novice group. The colour vision test results were therefore consistent with those of the other visual measures in indicating that the experts have normal but not supranormal vision, at least as assessed via standard optometric methods.

Tests of Hand-Eye Dominance Ocular dominance was measured with a simple sighting test as a precursor to classifying the subjects into two distinct hand-eye dominance categories. Unilateral hand-eye dominances (i.e., situations where the dominant eye and the dominant hand are on the same side of the body) might have been predicted to have been more prevalent in expert players than cross–lateral dominances (dominant eye and hand on opposite sides of the body) because the unilateral configuration allows a closer natural alignment of the dominant eye and the hand controlling the cue. In this sample of subjects unilateral dominance was equally prevalent in all three skill groups. In those subjects displaying clear ocular dominance 4 of 5 experts, 6 of 7 intermediates and 10 of 12 novices were unilateral.

TESTS RELATED TO SHOT EXECUTION AND WHAT THEY REVEALED

Tests of Force Consistency Control To ascertain if the development of movement consistency is an essential characteristic of the motor control of expert players, the players were given a task in which they were required to strike the cue ball up the table and rebound it off the top cushion with precisely the correct force to have the cue ball finish in the middle of the table. The task was repeated 10 times in succession and the consistency of cue control used by the subjects was examined by analysing the acceleration patterns of the cue. This was achieved through a miniature triaxial accelerometer mounted in the cue itself. In a second set of task conditions a further 10 repeat trials were given but in this case the goal was to impart sufficient force from the cue ball to an object ball to have the object ball finish precisely mid–table after rebounding off the top cushion. In both sets of tasks the cue ball was initially positioned on its normal spot for the start of any match. For the second task the object ball was located some 40cm directly in front of the cue ball. The interest was in ascertaining both how well the different skill groups could perform the two tasks and how their task performance was achieved with respect to the cue kinematics.

Not surprisingly the expert and intermediate group outperformed the novice group on both sets of tasks showing both greater accuracy (with respect to the desired finishing position) and greater trial-to-trial performance consistency. When the accelerations applied to the cue were analysed it was found that the experts displayed superior trial-to-trial consistency in the acceleration patterns produced in all three directions whereas the novice's cue control was characterized by high variability. The expert's restricted their force control almost exclusively to an axis directed down the line of the table, minimizing unnecessary force applications in either the lateral (across-the-table) or vertical direction. Accelerations in these other directions were greater for the poorer players. The force control produced by the experts therefore approximated an idealized model of control and efficiency where all force application was directly task relevant and all extraneous forces were minimized. The novice's cue control, in contrast, displayed not only greater variability but also greater inefficiency.

Interestingly all three skill groups in the study showed increased variability in the cue kinematics when the task complexity was increased to include an object ball, possibly providing objective evidence for Karnehm's (1976) observation about the effects of distraction upon cue control. The variability increase from the simpler cue ball task to the more complex object ball task was least for the expert performers, but nevertheless still significant.

Tests of Force Modulation Control It would appear logical to expect that the successful billiards and snooker player would need to not only be able to produce given levels of impact force (from cue to cue ball) with consistency but be also able to precisely adjust impact force levels to meet the 'touch' requirement of different shots. We tested this ability in our sample of players by two sets of tasks not dissimilar to those used to test force consistency control. In the first task the target position was systematically moved in 18 cm steps from a position in the centre of the table on trial 1 to a position only 21 cm from the far end of the table by trial 10 with the subject's goal being to modulate the force applied to the cue ball at impact so as to have the cue ball finish at the required target position for each particular trial. The second task had identical trial–to–trial variations in target position only the goal in this case was to position an object ball rather than the cue ball. Analyses of task performance and of the acceleration patterns of the cue were of principal interest.

Surprisingly both these tasks proved to be very difficult even for the expert players, to the extent that all three skill groups in the study were equally adept (or, perhaps more appropriately, inadept) at precisely modulating impact force on a trial–to–trial basis. For all the subjects attempts to adjust impact force were made primarily through alterations in the peak acceleration applied to the cue during the forward swing. Neither the backswing nor the downswing duration was systematically altered in response to the varying impact force requirements nor was there any proportional scaling of either the temporal or force dimensions of the cue kinematics evident. Attempts at force adjustment therefore appeared to be restricted to one point in the cue swing rather than distributed across the whole movement of the cue.

CONCLUSIONS REGARDING EXPERTISE IN BILLIARDS AND SNOOKER

As best our test battery can reveal, the locus of expertise in billiards and snooker appears to reside in the shot–selection and shot–execution stages of performance. Experts differ from novices at the shot–selection stage in having a greater ability to recall and recognize game–specific patterns of play, in undertaking more detailed forward planning of ongoing shot options and in evaluating situational opportunities more positively and prospectively. In the shot execution stage experts show superior force control consistency, minimizing extraneous forces applied in directions other than that in the desired direction down the line of the table. No expert–novice differences were apparent on any of the standard optometric measures administered to test for individual differences in visual alignment capability in the shot preparation stage of performance.

IMPLICATIONS FOR THE DEVELOPMENT OF EXPERTISE IN BILLIARDS AND SNOOKER

1. Given the value of the tests of pattern recall, pattern recognition, forward planning and situation evaluation (in the shot selection stage) and the test of force consistency control (in the shot execution stage) in discriminating expert from novice players these tests themselves would appear to be potentially valuable as both (a) yardsticks of skill acquisition and (b) components of any consolidated talent identification programme within billiards and snooker.

2. If skill acquisition is thought of as the process of developing expertise it would appear logical for coaches to direct their emphases in practice toward improvement in those elements which distinguish the expert performer from the lesser skilled[1]. In this case this involves a focus upon practising specific elements within the shot-selection and shot-execution components of billiards and snooker performance.

The shot-selection components are largely neglected elements of billiards and snooker skill and are certainly elements which are rarely systematically trained, despite their importance to expert performance. In light of the current test results there would appear to be value in:

- developing instructional materials, such as coaching videotapes, in which top-level players verbalize their thought processes regarding shot-selections, as this would provide a useful model to learners and exposure to the importance of extensive forward planning

- having developing players constantly 'talking aloud' their decision-making, so that instructors and coaches can facilitate the thorough consideration of all available options and the development of 'looking ahead' skills

- coaches highlighting similarities in play structure from one game to another in much the same way that chess teachers highlight and practice particular set pieces which are regularly occurring sub-components of the total game

- using available techniques of positive self-talk etc from sport psychology to focus the attention of beginning players on current and future elements of each game rather than dwelling on past events (as reflected in the current score) that are beyond the player's control.

With respect to the shot execution elements of performance there would also appear to be value in:

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[1] This argument assumes that the expert-novice differences that we have documented are, at least in part, a cause and not merely a by-product of skill in this sport.

- using the simple force consistency control tests described previously as an ongoing measure of skill acquisition

- developing inexpensive biomechanical feedback devises (based on a cue-mounted accelerometer) to help provide players with continuous and objective feedback regarding the desired cue acceleration consistency in the down-the-table direction and cue acceleration minimization in the lateral and vertical directions

- using sport psychology techniques, such as attentional control training, to offset the cue control variability which arises from the addition of other balls on the table as distractors.

3. The suggestions listed above are primarily suggestions that may aid the novice and lesser skilled player in becoming more expert-like. The relatively poor performance of all skill groups, experts included, on the force modulation control test, however, provides a hint as to at least one avenue through which the performance of the expert group might also be enhanced. As force modulation control is undoubtedly a persistent requirement of good billiards and snooker performance there may well be benefit in practising such control factors more systematically, perhaps using practice routines modelled on the test sequence used in this study.

4. The fact that the standard optometric tests of visual alignment, used in this study to examine the shot preparation phase, did not discriminate the expert players from the lesser skilled indicates that experts, like novices, are characterized more by normal than supranormal vision. This observation in turn suggests that, providing a player has normal (non-defective) levels of basic vision, there is little likelihood of improvements in playing performance being gained from the use of standardized visual training programs aimed at enhancing fundamental visual characteristics such

as acuity, depth perception and the like. Substantial benefits may be gained, however, if below–average vision is detected through regular optometric screening and then corrected, either via lens prescription or some form of vision therapy.

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Author Notes

Requests for reprints should be addressed by post to Robert Neal, Department of Human Movement Studies, University of Queensland, 4072, AUSTRALIA or by email to rn@brolga.cc.uq.oz.au

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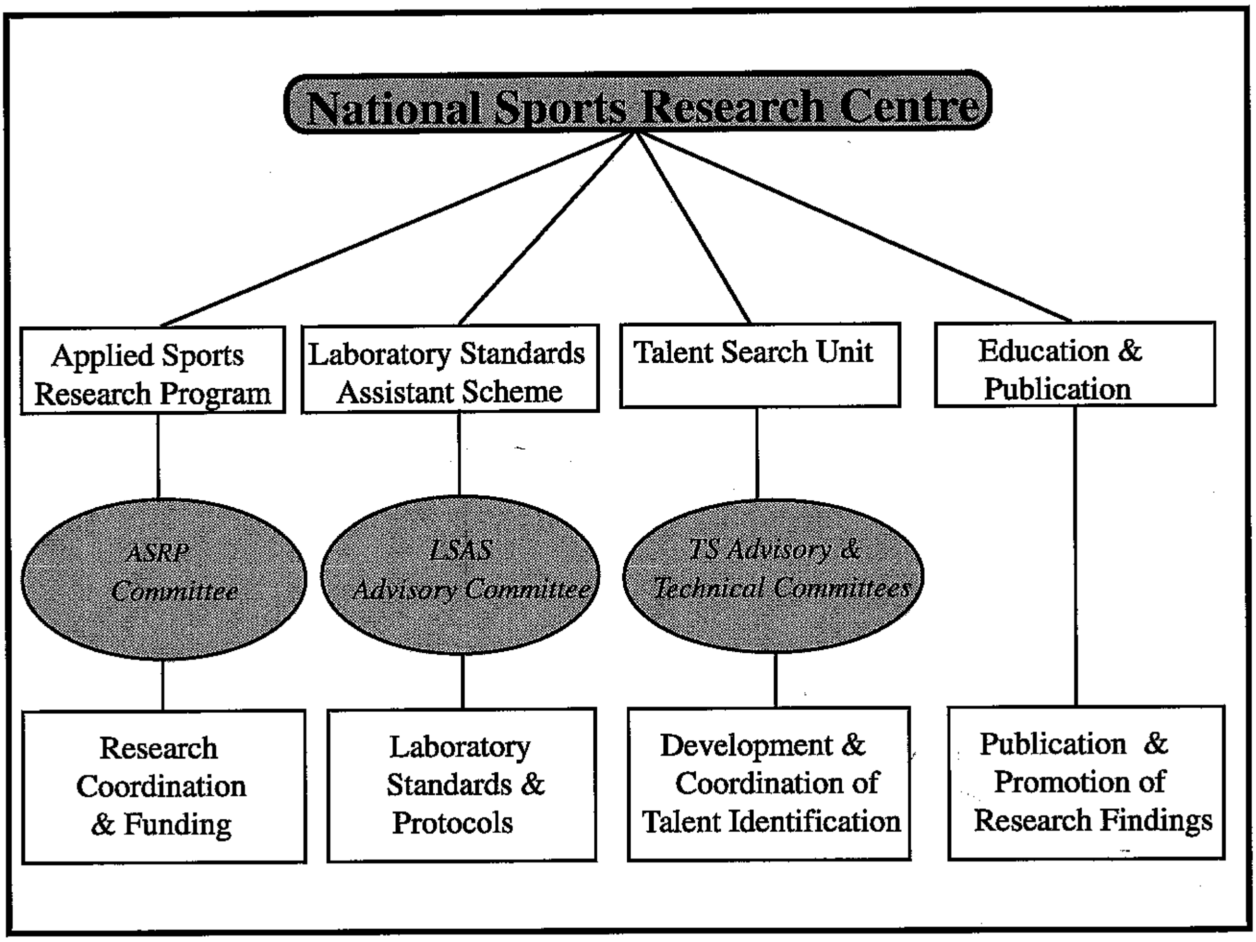

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