Investigating the paranormal

from David F. Marks

Parascience has so far failed to produce a single repeatable finding and, until it does, will continue to be viewed as an incoherent collection of belief systems steeped in fantasy, illusion and error.

FEW fields of inquiry capture the attention of the public as much as the paranormal. Newspapers, books, films and television have all cashed in and promoted it. Yet after millennia of experience and more than a century of controlled investigation, since the founding in 1882 of the Society of Psychical Research, the paranormal remains as controversial as ever. While credence in extrasensory perception (ESP) and precognition is widespread, parapsychology has failed to produce a single repeatable demonstration. In the face of such a dearth of hard evidence, how can such widespread belief in the paranormal be accounted for?

The importance of rigorous analysis of the evidence for parascientific claims cannot be underestimated. The establishment of ESP could conceivably require a paradigm shift (in Kuhn's sense) of the most fundamental kind and our concepts of mind–brain relationships and consciousness would need radical alteration. Our whole approach to psychology as an empirical science, based as it is on the time-honoured assumption that perception can result only from sensory activity, would be brought into question.

The conventional response of many scientists to the paranormal is to ignore the evidence on *a priori* grounds, believing it to be of basically poor quality. This attitude is allied to the Humean stance that a lie is more probable than a miracle. Although this scepticism is certainly justified, it could be argued that such a blanket response is counterproductive. First, it is hardly scientific to reject a claim purely because of its *a priori* improbability. Second, a division is created between aligned groups of committed 'believers' and 'sceptics' and the resulting adversarial positions inhibit proper discourse and the possibility of an account which satisfies all parties. Third, it leaves the field open for undisciplined exploitation, which is irresponsible; there are many examples of financial loss, suffering and even death resulting from fraudulent paranormal claims (for example, the Jonestown massacre, psychic surgery, the Transcendental Meditation levitation programme, firewalking, scientology and other pseudo-scientific cults). For scientists passively to ignore such developments is, to say the least, uncharitable.

The Committee for the Scientific Investigation of Claims of the Paranormal (CSICOP) was established in 1976 with the aim of increasing the quality of scientific investigations into the paranormal by constructive criticism and the exposure of invalid or fraudulent claims. Over this 10-year period, an inordinate amount of fraud, error and incompetence in paranormal investigations has been brought to light[1–11]. But pseudo-sciences are remarkably stable and tradition-bound; their presence on the edges of science can be expected indefinitely[12].

Areas of experimental psychology can shed light on the paranormal, especially the study of consciousness and cognition. Such investigation indicates that the many anomalies of putatively paranormal experience are an inevitable consequence of normal selective and constructive processes in perception, memory and imagery. I summarize here what seem to be the common assumptions on which claims of the paranormal are based.

Theoretical assumptions

Paranormal phenomena are negatively defined. A phenomenon is defined as paranormal only if it contravenes some fundamental and well-founded assumption of science. Hence, to establish an effect as paranormal, all possible 'normal' explanations must be shown to be invalid. Any paranormal claim thus also remains provisional; a normal explanation, not previously thought of, may be discovered at some future time.

Mysteriousness *per se* is a necessary but insufficient condition for adjudging an event as paranormal. There will always be limits to knowledge, so that new phenomena that initially appear anomalous will be given a natural explanation following systematically controlled observations. Bona fide paranormal effects, on the other hand, are supposed to contravene established assumptions as though from another order of existence and not simply for lack of explanation. 'Contranormal' would be a more precise technical term.

Examples of effects which until recently were claimed to be paranormal but which can now be explained from within orthodox science include:

(1) Kirlian photography, the photographic recording of coronal discharges around living or non-living objects produced by high-voltage, (20–100 kV), high-frequency (75 kHz–3 MHz) electrical fields[13,14]. Variations in the images of the corona can be explained in terms of normal physical factors such as moisture, pressure or distance, all of which influence circuit resistance.

(2) Fire-walking, if conducted briskly on hot materials of low thermal capacity and poor thermal conductivity, does not produce burns[15,16]. The Leidenfrost effect created by an insulating layer of water or sweat may also reduce energy transfer to the surface of the body.

(3) Dowsing is based on sensory cues, expectancy effects and probability. Controlled trials fail to produce above-chance results[8,17–19].

(4) Psychic surgery, thought photography and metal bending all involve sleight-of-hand and can be duplicated by skilled magicians[8,20–22]. The first differs from the others in respect of the associated false hopes and financial loss, but all three are fraudulent.

(5) 'Gellerized' watches[21,22], thought to be broken, are purportedly repaired by illusionist Uri Geller by 'psychic concentration'. In about 50% of cases, simply holding the watch in a clenched first and shaking it provides a sufficient stimulus to free the mechanism[23].

(6) Astrology, graphology, tea-leaf and tarot card readings, the I Ching and other forms of divination are all types of 'cold reading' or 'sleight-of-mouth'[24]. They depend upon ambiguous, wish-fulfilling and general advice, the use of prior or presented information and cues obtained by verbal 'fishing'. A strong feeling of personal validation often accompanies such readings. Various forms of 'mediumship' and 'psychometry' as practised by D. Collins and D. Stokes are also examples of cold reading.

In some cases, field observations can be checked under laboratory conditions and the sensori-motor features of the original performance reproduced using a delayed

control group of non-psychic subjects; for example, Geller's watch-starting procedure and ability to draw the contents of sealed and apparently opaque envelopes were matched by that of non-psychic controls[23] (Fig. 1). Clearly, the tendency to judge a mysterious event as paranormal in the absence of controlled observations can be quite misleading.

The most dramatic evidence for the paranormal has been based on either fraud or methodological error. Apparent frauds that have been uncovered include University of London mathematician S. G. Soal's manipulation of his recording sheets[25-27], University of Utrecht Professor Tanhaeff's evidence on Croiset, the Dutch 'psychic' detective[28], and the description by C. Castaneda (University of California at Los Angeles) of the paranormal teachings of Don Juan[29]. C. E. M. Hansel[3] has provided a valuable review of the history of trickery, fraud and error in parapsychology. However, outright fraud is not the only vehicle in which the paranormal cause can travel, and it is a serious mistake to assume it is a necessary part of any paranormal investigation.

There are no theories to account for paranormal effects or their properties. There are some undesirable implications of this aspect. First, investigators are unable to conduct properly controlled experiments on the properties of psi phenomena because they have no idea what the relevant variables are. In particular, there is no procedure by which psi can be deliberately switched on or off, and so there is no possibility of examinng the effects of psi on other variables. All that can be done is to establish whether a given performance in some particular set of circumstances differs from a baseline; if so, psi is assumed to be the cause.

Oddly, neither the subject nor the experimenter can state which of the successful trials in a psi experiment result purely from chance guessing and which are generated by psi, so that there is no basis for distinguishing between a high score in a psi experiment and a lucky run in a game of chance. Also, the persistence of psi investigators in the face of variable but mainly negative results could have a similar motivational basis to that of addicted gamblers; both show high resistance to extinction following variable ratio schedules of reinforcement[30].

A more fundamental problem with the paranormal's atheoretical status is that of untestability. Failure to observe a particular effect can be readily attributed to a host of *ad hoc*, hypothetical factors. Vivid imagination is no substitute for testability, however, and if *ad hoc* hypotheses are not independently testable, nor is the original claim[31].

It has been stated that the participants in any experiment may unconsciously determine the results according to whether they themselves believe in psi, the so-called 'sheep-goat' effect[32]. Hence, psi can be held to be present whatever the results, unless the belief of the investigators is itself independently controlled.

In an extreme version of the 'sheep-goat' hypothesis, some investigators have even proposed that the participants in an experiment need not be restricted to the individuals in the laboratory but could also include all of the readers of the journal which subsequently publishes the results[33]! In this case the proportion of sceptics and believers among the eventual readership would determine the experimental outcome through backward causality. Similar in kind is the 'shyness effect', the tendency of metal not to bend psychically while it is being observed[34].

Evidence of the paranormal is held to be incompatible with materialism. Investigators throughout history have been convinced that evidence of the paranormal proves that materialism must be wrong. This was assumed by the Society of Psychical Research, one of whose early presidents, Sir William Barrett, spoke of parapsychology 'as the most valuable handmaid to religion'[35]. J. B. Rhine[36], the founder of the Parapsychology Association and C. Tart[37], a former president, have both reiterated the religio-spiritual motive for pursuing psi research.

An immaterial 'soul' has passed out of the formal language of parapsychology, but anti-materialism is still the backbone of the underlying philosophy. A. Flew has described the profound logical difficulties with an immaterial, immortal entity which somehow discriminates its own mental experiences from that of all others[38]. But even putting that issue to one side, it is curious how seldom the anti-materialist assumption has been properly explained. D. E. Cooper indicated one way in which the anti-materialist argument can be constructed as a *reductio ad absurdum*, but he found this to be incoherent[39]. In fact, it seems doubtful that materialism and ESP would be incompatible, should real evidence of ESP ever be found. As M. Scriven has pointed out, materialism can always be enlarged to absorb newly substantiated phenomena, "since the very act of substantiation demonstrates that the phenomena are indeed part of the material world, and hence that a current version of materialism must embrace them[40]."

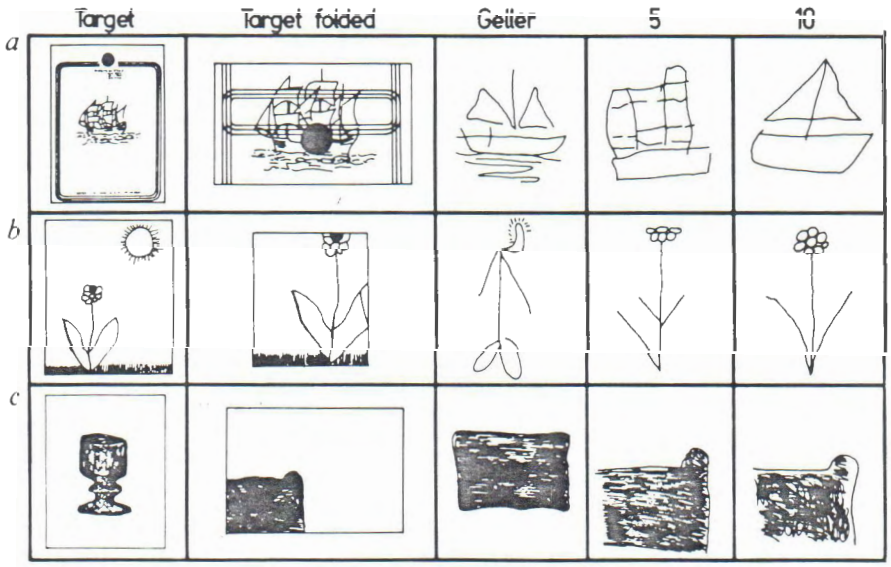

Fig. 1 Drawings presented to Geller and to non-psychic controls. The targets were inside envelopes, and Geller and the controls were allowed to see the sealed envelopes. The first and second columns show targets as they appeared in unfolded and folded states. Geller's final attempts at reproducing the drawings, which were folded and sealed inside envelopes, are shown in column 3. Columns 4 and 5 show the best results obtained from the control subjects after only 5 and 10 s of close visual inspection. The drawings were presented inside the same envelopes under similar lighting conditions. Geller, who claimed to use ESP, had taken 11.5, 85 and 18 min for *a*, *b* and *c*, respectively, but he was being observed, albeit discontinuously (see ref. 23).

Methodological problems

The failure of paranormal investigators to produce a single repeatable effect despite 100 years of published research is a serious matter. The hoped-for results have been described in thousands of reports, but not one can be repeated in a properly controlled replication. Yet in addition to the huge literature of unrepeatable findings, there is an inestimable number of unpublished and presumably negative results.

The most systematically investigated area is undoubtedly parapsychology. The field is professionally organized, with its own associations of accredited members and journals. Since 1969 the Parapsychological Association has been an affiliated division of the American Association for the Advancement of Science. On the sur-

face, the research sophistication of many parapsychologists seems to be as high as that of other professional researchers. The University of Edinburgh now has its own Koestler Chair of Parapsychology. Yet parapsychology is unique in that it remains permanently in search of a reliable finding. In spite of the long history of error, fraud and negative results, the practitioners remain confident that a positive result will soon be obtained. While many abortive leads have been reported in its major publications (for example, *Advances in Parapsychological Research*, *Handbook of Parapsychology*[41], *Journal of Parapsychology*), there is no paradigmatic experiment in the Kuhnian sense, and every new investigator must start afresh, as though he or she is the first worker in the field.

Leading parapsychologists acknowledge the unrepeatability and admit that no single experiment has been free of error. J. Beloff[42] and R. Morris[43] have concluded that the best case for psi rests on collections of experiments which, although individually flawed, reveal the undeniable presence of psi. But badly controlled experiments prove nothing, no matter how large the collection.

If any genuinely repeatable effect is ever discovered, then existing science would be modified to accommodate the new finding, which would then become an integral part of materialist science. The continued existence of 'parascience' as a separate field depends upon the investigators' creativity in searching for new, unexplained anomalies of a singularly unrepeatable kind.

How close are we to a repeatable paranormal finding? Examination of the literature suggests, not very. In systematic reviews of parapsychological experiments, C. Akers[44] and R. Hyman[45] have independently come to the same conclusion: that the research methods and evidence are too weak to establish the existence of a paranormal phenomenon.

Akers reviewed a representative sample of 54 published experiments which used unselected subjects and reported significant results. The sample included 11 experiments using the ganzfeld technique (in which the eyes and ears receive unpatterned sensory inputs), 12 hypnosis experiments, 12 studies of personality correlates, 10 studies of attitude correlates, 5 relaxation experiments and 4 meditation experiments. Akers identified seven sources of methodological error and the majority of experiments included one or more errors (see Table 1).

Hyman's analysis included 42 ganzfeld experiments reported during 1974–81. Twenty-three (55%) claimed significant evidence of psi on at least one performance measure. Giving consideration to what can be counted as an independent study, Hyman concluded that the true success rate was at most 31%. Moreover, many studies had conducted multiple statistical testing by analysing more than one performance measure and Hyman suggested that a more realistic significance level would have been as high as 0.25 instead of the nominal 0.05 level. Hence, the effective significance level and percentage of significant results are approximately equal.

Table 1 Flaw analyses of representative parapsychological experiments: proportions of samples containing each flaw

Flaw	Akers' sample (ref. 44)	Hyman's sample (ref. 45)
Sensory cues	22/54	23/42
Inadequate randomization	13/54	31/42
Inappropriate statistics or multiple testing	11/54	12/42
Potential fraud	12/54	10/42
Recording errors	10/54	—
Classification or scoring errors	9/54	—
Reporting failures	10/54	25/42
One or more errors	46/54	42/42

Hyman's tally of procedural flaws is shown in Table 1. None of his sample was judged to be free of flaws, while Akers adjudged only eight of his sample to be flawless, but stated that none could be considered ideal.

The much-publicized experiments on remote viewing by Puthoff and Targ[46] are also invalid because of the many sensory cues[47], non-randomization[47] and inappropriate statistics[48]. Tart organized a reanalysis of this research and claimed to have removed all of the sensory cues and obtained the same highly significant results[49]. However, he did not in fact remove all of the cues as he had stated. Attempted replications of the remote-viewing research are either flawed or, in the case of well-controlled studies, show no evidence of ESP[50].

This review leads to only one conclusion: there is no scientific evidence of ESP. Yet millions of people throughout the world believe in the reality of ESP and other paranormal phenomena. How can these two facts be reconciled? Is science mistaken, or are folk beliefs manufactured from error and illusion?

Psychological factors

Many factors of a psychological nature foster paranormal beliefs and make them a common feature of human thinking and behaviour. Our cultural traditions are steeped in religion and magic, many features of which lend themselves to belief in supernatural agencies. Scientific thinking is a recent departure in human history and scientific ideas have had little time to affect the magical thinking from which science itself evolved.

Sociologist D. O'Keefe argues that paranormal research has evolved from within the traditions of magic which themselves evolved from religion[51]. The current occult revival is seen as a reaction to the excessive rationalism which many perceive in science. O'Keefe argues that religion created the 'cloud-cuckoo land' in which magic, and thence the paranormal, can flourish. Yet scientists are often ill-prepared to provide the necessary counterbalancing rational account of the paranormal. Against this background of magico-religious entrenchment, there are some extra psychological processes that make paranormal beliefs an inevitable characteristic of human consciousness and thinking.

Mental imagery. A mental image is a quasi-perceptual experience in the absence of an objective stimulus. There are huge individual differences in the reported vividness and controllability of images. In Western cultures 1–5% of the population appears regularly to experience fantasies which seem as real as actual events even though they are entirely fictional[52]. Such individuals often experience vivid, uncontrollable 'eidetic' images of almost hallucinatory quality[53], are highly suggestible and can be easily hypnotized[52]. They report more putatively paranormal experiences, such as telepathy, precognition, ghosts and out-of-the-body experiences. While mental imagery has a large number of practical uses in thinking, memory and problem solving, it can also occur in altered states of consciousness in which the normal level of lucidity is no longer present[53].

Research conducted a century ago by E. Gurney and F. W. H. Myers described 27 cases of 'spirit communication' from deceased persons[54]. Eighteen of the apparitions occurred in sleep-related states normally associated with highly vivid and autonomous images which are easily mistaken for reality. The remaining cases occurred in subjects who were fully awake and these could easily have been structural eidetic images stimulated by thought-processes of the daydreaming kind[53]. H. Sidgwick noted that 9.9% of 17,000 subjects had experienced at least one vivid visual, auditory or tactile image of a living being or object while completely awake[55]. The appearance of ghosts is shaped by cultural expectancies and beliefs about what a ghost should look like[56]. Mental

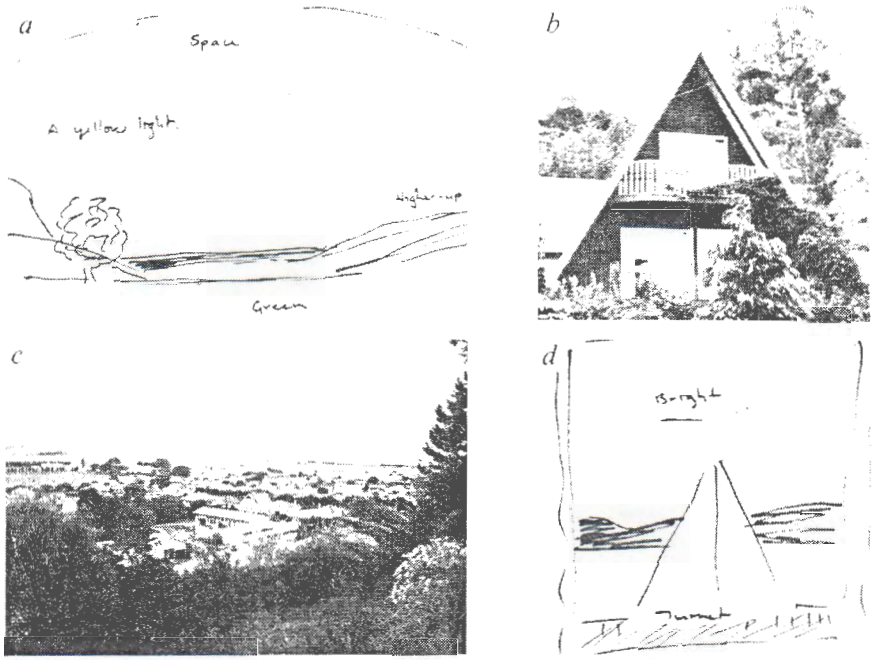

Fig. 2 *a*, A remote viewer's drawing of the target site shown in *b*, an A-frame house and steps, purportedly using ESP. When taken to the target area, the subject was delighted when he discovered the view from above the house, halfway up the steps (*c*). When an independent judge visited the target he was convinced that the correctly matching drawing was *d*. This had actually been produced for another target site, a railway station (see ref. 4).

images can be easily misinterpreted in terms of pre-existing beliefs[57].

Expectancy or mental set provides the framework within which we organize new experience. Human cognition is not a simple copying process but entails a constructive striving or 'effort after meaning'. What we experience is often more a confirmation of belief than a matter of plain fact. Beliefs are not automatically updated by the best evidence available, but have an active life of their own and fight tenaciously for their own survival. They tell us what to read, what to listen to, who to trust and how to rationalize contray information[4,5,57].

Selective exposure protects beliefs from more dramatic forms of contradiction. When the mentalist U. Geller visited the city of Dunedin in New Zealand there were seven different opportunities to obtain information abut his alleged psychic abilities: four media interviews, two newspaper stories and one stage performance. Of 17 subjects who, before Geller's visit, were already 'believers', 15 selected three or more of the available exposures. Of 20 'non-believers', only 10 selected as many as three exposures ($\chi^2(1) = 6.13$; $P < 0.02$).

A further problem is that when we are exposed to relevant information, our opinion revisions are often less than optimal, and we act like conservative Bayesians[58], with a confirmation bias[59]. In a recent 'ESP' demonstration to a class of 226 psychology students, presented as an exercise in observation, I performed five mentalists's tricks consisting of: (1) correctly naming a colour written out of sight; (2) correctly transmitting a colour name to a volunteer who, like me, had not previously seen it; (3) helping a volunteer correctly to read messages sealed inside envelopes or to appear to transmit messages to me; (4) producing bent keys which I had not previously touched; and (5) moving or stopping the hands of a watch in a mysterious manner.

Although at no time did I claim to be psychic, 90% of the class stated that I had demonstrated psychic ability. When the results from subjects who had previously been classified as 'believers' and 'sceptics' were analysed separately, 79% of believers thought at least three of the five effects were psychic compared with only 43% of sceptics ($P < 0.001$).

Naturally, we often encounter information that is unexpected or ambiguous. In such instances, there is a second line of defence: the data can be selectively perceived or even misperceived so that they still appear to support our beliefs by 'subjective validation'[4]. One illustration of this powerful cognitive defence in the context of ESP research is the strong conviction that one has successfully viewed a complex target site by ESP in a remote-viewing experiment even when one is completely wrong (Fig. 2).

There are many now-classic examples of subjective validation: the prophecies of the Delphic Oracle and Nostradamus[60], the discovery of N-rays[61], phlogiston, Vulcan, the canals on Mars, flying saucers, Freud's interpretation of dreams, prejudice, faith-healing, the placebo effect, bone pointing and the 'evil eye'. Beliefs of all kinds tend to be self-perpetuating.

Coincidences. Psi phenomena consist of an experience, image or thought matched by some other similar experience, image or thought. Collections of such coincidences have been published by A. Koestler[62], L. Rhine,[63] and others based on the assumption that odd-matches of events cannot occur purely by chance.

Probability theory shows that an event which is improbable over a short run can become highly probable over the long run. If five coins are tossed all at once on a single occasion the probability of obtaining five heads is 2^{-5} or approximately 0.03. If the coin tossing is repeated 100 times the probability of five heads somewhere in the series is approximately 0.96.

The principle of the long run is easy to grasp in simple situations but much less visible in the more chaotic world of spontaneous human experience. Calculation shows how easily Koestler could obtain his 40-plus odd-match anecdotes. Assuming that in an ordinary day a person can recall 100 distinct events, there are ${}^{100}C_2$ or 4,950 pairs of events per day. Odd-matches can be remembered for years, perhaps 10 yr or 3,650 days. If Koestler knew 1,000 people, he could draw upon a total pool of $4,950 \times 3,650 \times 1,000$, or more than 18×10^9 pairs of events. That Koestler obtained 40 striking odd-matches seems hardly surprising.

Koestler's fallacy (see ref. 4) is certainly not unique to him, although he was one of a small group of analysts who wanted to make a scientific revolution out of it. The fallacy is widespread and several biases contribute to it. First, we notice and remember odd-matches. Second, we do not notice non-matches. This triggers the short-run illusion that makes the odd-match seem improbable. Third, we are normally poor estimators of probabilities, especially for combinations of events.

Unseen causes. Another class of psychic-looking experiences is generated by invisible chains of cause and effect which bias the probabilities away from chance levels. Failure to randomize target stimuli properly in ESP experiments is a good example of this. Thus, Tart reported a successful ESP experiment in which his subjects learned to score above chance in guessing which of 10 digits was displayed by an apparatus in another room following the presentation of feedback[64]. The random number generator mistakenly avoided using the same digit twice in succession, a bias which is matched by the pervasive 'gambler's fallacy'. When Tart removed this bias, the 'ESP' also disappeared[65].

Another unseen factor, used by illusionists, is the 'population stereotype'. The performer 'sends a message' to the

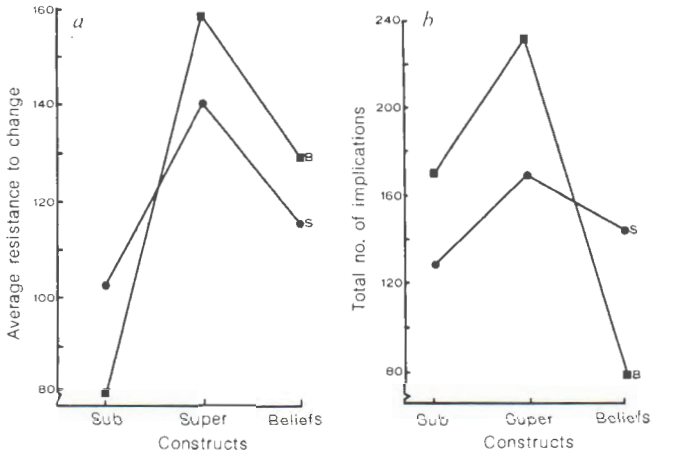

Fig. 3 *a*, The average resistance to change scores for 'believers' (B) and 'sceptics' (S) for subordinate (Sub), superordinate (Super) and belief constructs. Believers showed a significantly higher resistance to change for superordinate constructs than sceptics. *b*, The total number of implications for the same sets of constructs. The interaction between group and construct-type was highly significant ($F(2, 42) = 9.14$, $P < 0.005$). Believers saw significantly more implications in changing positions on superordinate constructs than did the sceptics, while sceptics saw significantly more implications in changing their beliefs than believers ($P < 0.05$ for both comparisons).

audience, saying "I am thinking of a number between 1 and 50, both digits are odd, and different". Controlled experiments show that the most common response for the 1-50 problem is 37, which accounts for 30-35% of all responses, and the second most common response is 35 (20-25%)[4]. If the performer always says he had been thinking of 35 and then changed his mind to 37, at least 50% of the audience will be thinking of the 'correct' number.

Human beings never behave randomly. Our experiences contain many culturally shared elements such that particular items are associated with particular verbal contexts. This causes associative networks to be set up and a tendency towards non-random, stereotypical responses even when there is freedom to choose.

Other unnoticed causes of putatively psychic effects include subliminal and non-verbal sensory cues[66] which may lead to common thought patterns in different people, presenting the illusion of telepathy.

The 'will to believe'. What factors differentiate believer from sceptic? Psychologists down the ages have puzzled over the question of what motivates different world-views and the so-called will to believe. Research conducted by J. Waugh used Kelly's personal construct theory. In this framework[67], people vary in the quality and extent of their investigatory procedures so that, while some may be working to establish an ordered and meaningful world which is not highly predictable or readily explained, others may be content that they already have all the necessary explanatory constructs.

In Kelly's theory, each individual deals with the world in terms of a hierarchial system of constructs with which people, objects and events are compared, contrasted and predicted. Core constructs have relatively superordinate positions and a large range of convenience while peripheral constructs are relatively subordinate and more easily altered. Waugh compared the personal construct systems of sceptics and believers in the paranormal using a belief questionnaire. Ten subordinate and ten superordinate[67] constructs were generated using standard procedures and each subject's constructs were tested for their relative resistance to change and the number of implications entailed by changing the subject's preferred pole on the 20 constructs and 10 paranormal beliefs (Fig. 3).

Believers' core constructs were significantly more resistant to change and there was a parallel difference in the number of implications resulting from changes at the superordinate level. Compared with sceptics, believers seem to possess much tighter construct systems in which any change at the core level implies a significantly greater upheaval or threat. Waugh also found that believers had significantly higher neuroticism scores than sceptics (see also ref. 68). These data are congruent with those reported by Zusne and Jones[57] who found that believers are less flexible than sceptics when confronted with disconfirming evidence. Content analyses of believers' construct systems indicate the presence of spiritual, non-materialist constructs at superordinate level. Such core constructs are not easily shaken because they are closed off from empirical considerations and appear to be impermeable to rational persuasion. Hence the feeling of futility experienced in trying to hold rational discussion between believer and sceptic; one could well be arguing about the existence of God. Belief in the paranormal is metaphysical and therefore not subject to the constraints of empirically based science.

Parascience has all the qualities of a magical system while wearing the mantle of science. Until any significant discoveries are made, science can justifiably ignore it, but it is important to say why: parascience is a pseudo-scientific system of untestable beliefs steeped in illusion, error and fraud.

I thank Jerry Andrus, Bob Audley, Ray Hyman, A. R. Jonckheere, Peter McKellar, J. Randi, Christopher Scott, Jean Waugh and many colleagues in CSICOP for useful discussions and information. The late Richard Kammann contributed substantially in the earlier stages of this research.

David F. Marks is at the Department of Psychology, University of Otago, PO Box 56, Dunedin, New Zealand.

1. Kurtz, P. *Skeptical Inquirer* **3**, 14-32 (1978).
2. Diaconis, P. *Science* **201**, 131-136 (1978).
3. Hansel, C. E. M. *ESP and Parapsychology: A Critical Reevaluation* (Prometheus, Buffalo, 1980).
4. Marks, D. & Kammann, R. *The Psychology of the Psychic* (Prometheus, Buffalo, 1980).
5. Alcock, J. E. *Parapsychology: Science of Magic?* (Pergamon, Oxford, 1981).
6. Frazier, K. (ed.). *Paranormal Borderlands of Science* (Prometheus, Buffalo, 1981).
7. Gardner, M. *Science Good Bad and Bogus* (Prometheus, Buffalo, 1981).
8. Randi, J. *Flim-Flam! Psychics, ESP, Unicorns, and Other Delusions* (Prometheus, Buffalo, 1982).
9. Kurtz, P. *Skeptical Inquirer* **8**, 239-246 (1984).
10. Frazier, K. (ed.) *Science Confronts the Paranormal* (Prometheus, Buffalo, 1985).
11. Kurtz, P. (ed.) *A Skeptics Handbook of Parapsychology* (Prometheus, Buffalo, 1985).
12. Bunge, M. *Skeptical Inquirer* **9**, 36-46 (1984).
13. Tiller, W. A. *New Scient.* **62**, 160-163 (1974).
14. Pehek, J. O., Kyler, H. J. & Faust, D. L. *Science* **194**, 263-270 (1976).
15. Houdini *Miracle Mongers and Their Methods* (Prometheus, Buffalo, 1981).
16. Leikind, B. J. & McCarthy, W. J. *Skeptical Inquirer* **10**, 23-34 (1985).
17. Vogt, E. H. & Hyman, R. *Waterwitching USA* 2nd edn (Chicago University Press, 1979).
18. Randi, J. *Skeptical Inquirer* **8**, 329-333 (1984).
19. Martin, M. *Skeptical Inquirer* **8**, 138-140 (1983).
20. Randi, J. *The Magic of Uri Geller* (Ballantine, New York, 1975).
21. Fuller, U. *Confessions of a Psychic* (Karl Fulves, Box 433, Tearleck, New Jersey, 1975).
22. Fulves, U. *Further Confessions of a Psychic* (Karl Fulves, New Jersey, 1980).
23. Marks, D. & Kammann, R. *Zetetic* **1**(2), 9-17 (1977).
24. Hyman, R. *Zetetic* **1**(2), 18-37 (1977).
25. Soal, S. G. & Goldney, K. M. *Proc. Soc. psychical Res.* **47**, 21-150 (1943).
26. Scott, C. & Haskell, P. *Nature* **245**, 52-54 (1974).
27. Marwick, B. *Proc. Soc. psychical Res.* **56**, 250-281 (1978).
28. Hoebens, P. H. *Skeptical Inquirer* **6**, 32-40 (1981).
29. De Mille, R. *Castandeda's Journey* 2nd ed (Capra, Santa Barbara, 1978).
30. Skinner, B. F. *Science and Human Behavior* (Macmillan, New York, 1953).
31. Bunge, M. *Method, Model and Matter* (Reidel, Dordrecht, 1973).
32. Schmeidler, G. R. & McConnell, R. A. *ESP and Personality Patterns* (Yale University Press, 1958).
33. Collins, H. M. & Pinch, T. J. *Frames of Meaning: The Social Construction of Extraordinary Science* (Routledge & Kegan Paul, London, 1982).
34. Taylor, J. *Superminds: An Inquiry into the Paranormal* (Macmillan, London, 1975).
35. Barratt, W. *Proc. Soc. psychical Res.* **34**, 275-297 (1924).
36. Rhine, J. B. *The Reach of Mind*, 209-214 (Sloane, New York, 1947).
37. Tart, C. T. *Psi: Scientific Studies of the Psychic Realm*, vii-viii (Dutton, New York, 1977).
38. Flew, A. in *Science, Pseudo-Science and Society* (eds Hanen,

M. P., Osler, M. J. & Weyant, R. G.) 55–75 (Wilfrid Laurier University Press, Waterloo, 1980).
39. Cooper, D. E. in *Philosophy and Psychical Research* (ed. Thakur, S. C.) 59–80 (Allen & Unwin, London, 1976).
40. Scriven, M. in *Philosophy and Psychical Research* (ed. Thakur, S. C.) 181–194 (Allen & Unwin, London, 1976).
41. Wolman, B. J. (ed.) *Handbook of Parapsychology* (Van Nostrand, New York, 1977).
42. Beloff, J. *Zetetic Scholar* **6**, 90–94 (1980).
43. Morris, R. L. *J. Am. Soc. psychical Res.* **74**, 425–443 (1980).
44. Akers, C. in *Advances in Parapsychological Research* Vol. 4 (ed. Krippner, S.) 112–164 (McFarland, Jefferson, North Carolina, 1984).
45. Hyman, R. *J. Parapsychol.* **49**, 3–49 (1985).
46. Targ, R. & Puthoff, H. E. *Nature* **252**, 602–607 (1974).
47. Marks, D. F. & Kammann, R. *Nature* **274**, 680–681 (1978).
48. Hyman, R. *Skeptical Inquirer* **9**, 125–145 (1984–5).
49. Tart, C. T., Puthoff, H. E. & Targ, R. *Nature* **284**, 191 (1980).
50. Marks, D. F. *Skeptical Inquirer* **6**, 18–29 (1982).
51. O'Keefe, D. *Stolen Lightning* (Robertson, Oxford, 1982).
52. Wilson, S. C. & Barber, T. X. in *Imagery: Current Theory, Research and Application* (ed. Sheikh, A. A.) 340–387 (Wiley, New York, 1983).
53. Marks, D. & McKellar, P. *J. mental imagery* **6**, 1–124 (1982).
54. Gurney, E. & Myers, F. W. H. *Proc. Soc. psychical Res.* **5**, 403–485 (1889).
55. Sidgwick, H. *Proc. Soc. psychical Res.* **10**, 25–422 (1894).
56. Finucane, R. C. *Appearances of the Dead*. (Prometheus, Buffalo, 1985).
57. Zusne, L. & Jones, W. H. *Anomalistic Psychology* (Erlbaum, Hillsdale, New Jersey, 1982).
58. Edwards, W. in *Formal Representation of Human Judgement* (ed. Kleinmuntz, B.) 17–52 (Wiley, New York, 1968).
59. Nisbett, R. & Ross, L. *Human Inference: Strategies and Shortcomings of Social Judgment* (Prentice-Hall, Englewood Cliffs, 1980).
60. Hoebens, P. H. *Skeptical Inquirer* **1**, 38–45 (1982).
61. Klass, P. J. *Zetetic* **2**, 57–61 (1977).
62. Koestler, A. *The Roots of Coincidence* (Hutchinson, London, 1972).
63. Rhine, L. E. *J. Parapsychol.* **15**, 164–190 (1951).
64. Tart, C. T. *Learning to Use Extrasensory Perception* (University of Chicago Press, 1976).
65. Tart, C. T., Palmer, J. & Redington, D. J. *J. Am. Soc. psychical Res.* **73**, 151–165 (1978).
66. Dixon, N. F. *Preconscious Processing* (Wiley, Chichester, 1981).
67. Fransella, F. & Bannister, D. *A Manual for Repertory Grid Technique* (Academic, London, 1977).
68. Windholz, G. & Diamant, L. *Bull. psychon. Sci.* **3**, 125–126 (1974).

REVIEW ARTICLE

Heavy-electron metals

Z. Fisk, H. R. Ott*, T. M. Rice* & J. L. Smith

Center for Materials Science, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

A new class of metals has been found in which the electrons have effective masses orders of magnitude larger than the free-electron mass. Some of these metals are superconducting at low temperatures. This superconductivity seems to be unconventional, with an underlying mechanism different from that in all other known superconductors.

AMONG the main developments in physics since the 1930s have been the discovery and exploration of new ground states of condensed matter. Each of these discoveries opened a new chapter in the physics of condensed matter; recent examples are spin- and charge-density waves in metals, the superfluid state of liquid ^{3}He and the quantized Hall effect. Very recently an exciting new class of metallic materials has been discovered with remarkable properties and showing signs of further new ground states. (A general compilation of data, with references current as of mid-1984, can be found in ref. 1.)

The terms 'heavy-electron metal' and 'heavy-fermion system' have been introduced to describe materials in which the electronic states have a characteristic energy orders of magnitude smaller than in ordinary metals. If we write the energy $\varepsilon(k)$ in a free-electron form ($\varepsilon(k) = \hbar^2 k^2/2m^*$), then since the wavevectors $\mathbf{k}$ of the electron determined by the interatomic spacing are not much different, the effective mass m^* must be orders of magnitude larger than the free-electron value and in some cases m^* is a fair fraction of the proton mass. These materials are intermetallic compounds in which one of the constituents is a rare-earth or actinide atom, with partially filled 4f- or 5f-electron shells. At high temperatures these materials behave as if the f-electrons were localized on their atomic sites, as in conventional rare-earth and actinide compounds, where any itinerant electrons are in states derived from loosely bound atomic s-, p- and d-orbitals. As the conventional materials are cooled, the atomic moments due to the f-electrons order spontaneously, mostly antiferromagnetically, less often ferromagnetically. By contrast, in the heavy-electron systems some of the f-electrons become itinerant at low temperatures and form a metallic state with the characteristics described above.

Recently the exciting discovery was made that in some of these new materials the heavy electrons form a superconducting state at very low temperatures[3,4,6]. Superconductivity in ordinary metals is associated with an instability of itinerant electrons; thus it was surprising that it should also occur where normal-state properties are dominated by nearly localized electrons. Various features of this superconducting state are unusual, leading theorists to speculate that not only is the mechanism driving this superconducting transition unconventional, but also that the configuration of the superconducting state is different from that of an ordinary superconductor. Instead of an interaction between electrons that is mediated by phonons (lattice-vibrational quanta), which leads to an essentially isotropic gap in the spectrum of electronic excitations, it is envisaged that a Coulomb interaction between heavy electrons induces a superconducting state in which the energy gap is strongly anisotropic. If this could be definitely established, it would be the culmination of a long search for this phenomenon.

There is no doubt that a proper understanding of this superconducting state requires a clear understanding of the preceding normal state with its remarkable properties. Early theories of the properties of metals always assumed that, whereas the conduction electrons interact with the ionic lattice forming the solid, they do not interact at all among themselves. Quantum statistics then determine the low-temperature properties of this electron gas, two of which are of particular importance in the context of our discussion. The specific heat of this electron gas c_p varies linearly with temperature as $T \to 0$ K (that is, $c_p = \gamma T$). The low-temperature magnetic susceptibility, χ, is independent of temperature. In this simple theory the ratio

$$\chi/\gamma = 3\,\mu_B^2/\pi^2 k_B^2 \qquad (1)$$

is obviously a universal number. $\mu_B = 9.27 \times 10^{-21}$ erg G^{-1} is the Bohr magneton and $k_B = 1.38 \times 10^{-16}$ erg K^{-1} is the Boltzmann constant. The factor which determines the magnitude of both χ and γ is the density of electronic states per unit energy, $N(E_F)$, at the Fermi energy E_F. (E_F is the energy up to which all possible states of the electron gas are occupied at $T = 0$ K.) Hence $N(E_F)$ varies inversely with the characteristic energy of the electrons, leading $N(E_F)$ to be proportional to m^*. This simple concept is quite adequate to describe the qualitative low-temperature features of simple metals, for which γ is of the order of 1 mJ mol^{-1} K^{-1}, $\chi \simeq 10^{-5}$ e.m.u. mol^{-1} and $T_F = E_F/k_B$, the Fermi temperature, is $\sim 10^4$–10^5 K. The experimental facts quoted in

* Permanent address: Eidg. Tech. Hochschule, ETH-Hönggerberg, CH-8093 Zürich, Switzerland.