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Attention and awareness in stage magic: turning tricks into research

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Abstract | Just as vision scientists study visual art and illusions to elucidate the workings of the visual system, so too can cognitive scientists study cognitive illusions to elucidate the underpinnings of cognition. Magic shows are a manifestation of accomplished magic performers' deep intuition for and understanding of human attention and awareness. By studying magicians and their techniques, neuroscientists can learn powerful methods to manipulate attention and awareness in the laboratory. Such methods could be exploited to directly study the behavioural and neural basis of consciousness itself, for instance through the use of brain imaging and other neural recording techniques.

Magic is one of the oldest and most widespread forms of performance art[1] (FIG. 1). It is also a discipline with a long legacy of informal experimentation. This informal research by magicians aims to determine what conditions allow for the maximum manipulation of human attention and perception. Much as early filmmakers experimented with editing techniques to determine which technique would communicate their intent most effectively, magicians have explored the techniques that most effectively divert attention or exploit the shortcomings of human vision and awareness. As such, magic is a rich and largely untapped source of insight into perception and awareness. Insofar as the understanding of behaviour and perception goes, there are specific cases in which the magician's intuitive knowledge is superior to that of the neuroscientist. In this Perspective, we underline potential areas in which neuroscientists stand to reap great benefits from collaboration with the magic community (BOX 1 highlights one such potential area of collaboration).

Using completely natural means, magicians create effects (magic tricks) that seem to be outside the laws of nature. One should note that, unlike so-called psychics, magicians do not claim to possess supernatural powers. The devices used by magicians can include one or more of the following: visual illusions (after-images), optical illusions ('smoke and mirrors'), cognitive illusions (inattentional blindness), special effects (explosions, fake gunshots, *et cetera*), and secret devices and mechanical artifacts (gimmicks).

Visual illusions — and other sensory illusions — are phenomena in which the subjective perception of a stimulus does not match the physical reality of the stimulus. Visual illusions occur because neural circuits in the brain amplify, suppress, converge and diverge visual information in a fashion that ultimately leaves the observer with a subjective perception that is different from the reality. For example, lateral inhibitory circuits in the early visual system enhance the contrast of edges and corners so that these visual features seem to be more salient than they truly are[2–6]. Unlike visual illusions, optical illusions do not result from brain processes: they manipulate the physical properties of light, such as reflection (using mirrors) and refraction (a pencil looks broken when it is placed upright in a glass of water owing to the different refraction indices of air and water). Cognitive illusions can be distinguished from visual illusions in that they are not sensory in nature: they involve higher-level cognitive functions, such as attention and causal inference (most coin and card tricks used by magicians fall into this category).

The application of all these devices by the expert magician gives the impression of a 'magical' event that is impossible in the physical realm (see TABLE 1 for a classification of the main types of magic effects and their underlying methods). This Perspective addresses how cognitive and visual illusions are applied in magic, and their underlying neural mechanisms. We also discuss some of the principles that have been developed by magicians and pickpockets throughout the centuries to manipulate awareness and attention, as well as their potential applications to research, especially in the study of the brain mechanisms that underlie attention and awareness. This Perspective therefore seeks to inform the cognitive neuroscientist that the techniques used by magicians can be powerful and robust tools to take to the laboratory. The study of the artistic intuitions that magicians have developed about attention and awareness might further lead to significant new scientific insights into their neural bases.

Visual illusions in magic

Visual illusions are often used by neuroscientists to dissociate the neural activity that matches the perception of a stimulus from the neuronal activity that matches the physical reality. Those neurons, circuits and brain areas with activity that matches the physical stimulus rather than the subjective perception can be excluded from the neural correlates of consciousness. Visual illusions are also used by magicians to fool their audiences, often to enhance cognitive illusions. Here we discuss a few categories of visual illusions that have contributed to magic tricks, as well as their neural bases.

Spoon bending. In this illusion the magician bends a spoon, apparently by using the power of the mind. In one part of the trick, the magician holds the spoon horizontally and shakes it up and down. This shows that the neck of the spoon has apparently become flexible[7]. The apparent rubberiness of the spoon is an example of the Dancing Bar

Figure 1 | **The Conjurer, by Hieronymus Bosch.** A magician performs for the crowd in medieval Europe, while pickpockets steal the spectators' belongings. The painting is in the Musée Municipal in St.-Germain-en-Laye, France.

(or Rubber Tree) illusion[8], in which an oscillating bar (or rubber tree) seems to bend when it is bounced rapidly. The neural basis of this illusion lies in the fact that end-stopped neurons (that is, neurons that respond both to motion and to the terminations of a stimulus' edges, such as corners or the ends of lines) in the primary visual cortex (area V1) and the middle temporal visual area (area MT, also known as area V5) respond differently from non-end-stopped neurons to oscillating stimuli[8–11]. This differential response results in an apparent spatial mislocalization between the ends of a stimulus and its centre, making a solid object look like it flexes in the middle.

The Retention-of-Vision Vanish. Persistence of vision is an effect in which an image seems to persist for longer than its presentation time[12–14]. Thus, an object that has been removed from the visual field will still seem to be visible for a short period of time. The Great Tomsoni's (J.T.) Coloured Dress trick, in which the magician's assistant's white dress instantaneously changes to a red dress, illustrates an application of this illusion to magic. At first the colour change seems to be due (trivially) to the onset of red illumination of the woman. But after the red light is turned off and a white light is turned on, the woman is revealed to be actually wearing a red dress. Here is how it works: when the red light shuts off there is a short period of darkness in which the audience is left with a brief positive after-image of the red-dressed (actually white-dressed but red-lit) woman. This short after-image persists for enough time to allow the white dress to be rapidly removed while the room is still dark. When the white lights come back, the red dress that the assistant was always wearing below the white dress is now visible.

This same illusion is the basis for perceptual stability during the viewing of motion pictures (the image seems to be stable when in fact it is flickering). On a neural level, both turning on and turning off a stimulus generate responses in visual neurons that result in the perceptual visibility of the stimulus[15]. The neural response that is generated by turning off a stimulus is called the after-discharge, and it has the perceptual consequence of a positive after-image that persists for approximately 100 ms after the termination of the stimulus[16–18].

Jerry Andrus's Trizonal Space Warp. In this illusion the audience stares for several seconds at a spinning disk with three zones of expanding and contracting motion. They are then asked to look at a different object on stage that consequently seems to both expand and contract. Motion after-effects, more commonly known as The Waterfall Illusion, are the oldest-recorded visual illusions. First reported in his Parva Naturalia, Aristotle noticed that if one fixates a moving stream of water and then looks away, the rocks at the side of the stream will seem to move in the opposite direction to the water. This effect is caused by neural adaptation — that is, by the decrease in responsiveness of a neural system to a constant stimulus. In the Trizonal Space Warp illusion, adaptation to expanding and contracting motion occurs in three different parts of the visual field.

The above illusions are examples of magic tricks that could have been used to help elucidate the underpinnings of visual perception. There might be other fundamental visual processes that could be discovered by studying magic (BOX 1). Further, we propose that there are cognitive processes that will be better understood as we learn more from magicians, as discussed in the next section.

Cognitive illusions in magic

Inattentional blindness and change blindness. Attended objects can seem to be more salient or to have higher contrast than unattended objects[19–22]. These perceptual effects have well-documented neural correlates in the visual system[23]. Magicians use the general term 'misdirection' to refer to the diversion of the spectator's attention away from a secret action. Thus, misdirection can be defined as drawing the audience's attention away from the 'method' (the secret behind the 'effect') and towards the effect (what the spectator perceives)[7,24]. Misdirection can be applied in an overt or a covert manner. Here we use the term 'overt misdirection' to indicate cases in which the magician redirects the spectator's gaze away from the method. In the more subtle 'covert misdirection', the magician draws the spectator's attentional spotlight (which can be thought of as the spectator's focus of suspicion) away from the method without redirecting the spectator's gaze. Thus, in covert misdirection the spectators can be looking directly at the method behind the trick and yet be unaware of it because their attention is focused elsewhere.

The concept of covert misdirection is exemplified by the cognitive-neuroscience paradigms of change blindness and inattentional blindness. With change blindness, people fail to notice that something is different from the way it was before. This change can be expected or unexpected, but the key is that it requires the observer to compare the post-change state with the pre-change

Box 1 | **Pickpockets pick your brain**

One area of neuroscience research in which magicians might have stolen the show is the dynamic control of attentional focus. One of the authors of this Perspective (A.R.) is a professional thief, and he reports that as part of his formal (albeit illegal) training he was taught how to move his hands so as to draw the attention of his 'mark', or victim, in specific ways according to the particular conditions of the robbery (see also Supplementary information S3 (movie)). Specifically, pickpockets move their hands in a curvilinear motion to misdirect the attention of the mark along the curvilinear trajectory, whereas they move their hands in a fast linear fashion to invoke fast attentional shifts from one spatial location to another, which serves to reduce the strength of the attentional focus. The neuroscientific underpinnings of these effects are unknown, but here we propose several possibilities that could be tested empirically.

One possibility is that these effects are due to differential engagement of the smooth pursuit and saccadic oculomotor systems. The curvilinear motion could draw the mark's oculomotor system into a long pursuit of the pickpocket's wandering hand; the foveal centre of vision would then follow the length of the trajectory, presumably dragging the attentional spotlight along with it. The fast straight motion could invoke a saccadic eye movement, and the suppression of visual perception that is known to occur during saccades[91–93] might result in reduced attention.

A second possibility is that, rather than the oculomotor system being differentially affected by the two types of motion, curvilinear target motions might be perceptually more salient than linear target motions, irrespective of eye movements. Curves and the corners of object surfaces are perceptually more salient and generate stronger neural activity than straight edges, possibly owing to the fact that they are less redundant and predictable (and therefore more novel and informative)[2–4]. This decreased-redundancy argument might also apply to non-predictable object-motion trajectories. If this is the case, curvilinear motion trajectories should be more salient (and consequently engage stronger attention) than straight trajectories.

The above possibilities are not mutually exclusive. Further, it could also be that the pickpocket's intuition is incorrect, and that different motion trajectories do not differentially engage the observer's attention. Either way, the empirical assessment of these issues would lead to novel scientific findings of potential significance. Thus, this subject is one of many into which neuroscientists might gain insight from the study of magic.

state. Change-blindness studies have shown that dramatic changes in a visual scene will go unnoticed if they occur during a transient interruption[25], such as a blink[26], a saccadic eye movement[27] or a flicker of the scene[28–31], even when people are looking right at the changes. However, observers can also miss large gradual changes in the absence of interruptions[32]. A dramatic example of change blindness is illustrated in the Colour-Changing Card Trick video by Richard Wiseman and colleagues (available online at YouTube.com). In this demonstration, the viewers fail to notice colour changes that take place off-camera.

With inattentional blindness, people fail to notice an unexpected object that is fully visible in the display. Thus, inattentional blindness differs from change blindness in that no memory comparison is needed — the missed object is fully visible at a single point in time. In a classic example of inattentional blindness, Simons and Chabris[33] asked observers to count how many times the members of a basketball team passed a ball to one another, while ignoring the passes made by members of a different team. While they concentrated on the counting task, most observers failed to notice a person wearing a gorilla suit walk across the scene (the gorilla even stops briefly at the centre of the scene and beats its chest!). In this situation no acute interruption or distraction was necessary, as the assigned task of counting passes was absorbing. Further, the observers had to keep their eyes on the scene at all times in order to accurately perform the task. Memmert showed, using eye-tracking recordings, that many observers did not notice the gorilla even when they were looking directly at it[34].

The magic community considers the covert form of misdirection to be more elegant than the overt form[7]. Few studies have addressed their relative efficacy, however. Kuhn and Tatler[35] measured the eye movements of observers during the presentation of a magic trick (a magician made a cigarette 'disappear' by dropping it below the table). To our knowledge, this is the first study to have correlated the perception of magic with any physiological measurement. The goal of the experiment was to analyse the scan paths of subjects to determine whether observers missed the trick because they did not look at it at the right time or because they did not attend to it (irrespective of the position of their gaze). The results showed that the detection (or not) of the cigarette drop could not be explained at the level of the retina. That is, detection rates were not significantly influenced by blinks, saccadic movements or how far the cigarette was from the centre of vision at the time of the drop. The authors concluded that the magician primarily manipulates the spectators' attention rather than their gaze, using similar principles to those that are used in inattentional-blindness studies. Thus, to overcome the magician's misdirection, spectators should reallocate their attention — rather than their gaze — to the concealed event (that is, the cigarette drop) at the critical time[36]. Recent studies have found that the directions of microsaccades can also be used as an indicator of the spatial allocation of covert attention[37–39]. Future research could aim to measure the microsaccade direction biases of spectators during successful and unsuccessful magic tricks.

A recent study of the Vanishing-Ball Illusion further supports the conclusion that the manipulation of gaze position is not critical for effective covert misdirection. In the Vanishing-Ball Illusion, a ball thrown by the magician vanishes mid-flight. To achieve this effect, the magician begins by tossing the ball straight up in the air and catching it several times without event; then, on the final toss, the magician only pretends to throw the ball. The ball is in reality hidden in the magician's hand, but most spectators perceive it ascending and then vanishing mid-flight. During the execution of this trick, the magician's head and eyes follow the trajectory of an imaginary ball being thrown upwards. Kuhn and Land[40] found that the magician's use of such social cues was critical for making the spectators' perceive the illusion (that is, the ball vanishing mid-flight). However, observers did not direct their gaze to the area in which they claimed to have seen the ball vanish, suggesting that the oculomotor system is not fooled by the illusion. Instead, the illusory effect is presumably caused by covert redirection of the attentional spotlight to the predicted position of the ball. This result is consistent with previous studies that suggested that there are separate mechanisms for perception and visuomotor control[41–48]. For instance, the eye movements of blindsight patients are biased towards stimuli that the patients do not consciously perceive[49–51]. Kuhn and Land[40] further proposed that in the Vanishing-Ball Illusion the covert redirection of the attentional spotlight to the predicted position of the ball might be related to "representational momentum" (REF. 52). That is, that the final position of a moving object that suddenly disappears is perceived further along the path of motion than its actual final position. The neural correlates of representational momentum might be located in the posterior parietal cortex in the primate[53]. Observers of the Vanishing-Ball Illusion might also be tricked by the strong implied motion that is suggested by the magician's moves. Recent studies have focused on the neuronal mechanisms that underlie the perception of implied motion (some examples of implied motion are the speed lines that are used by cartoonists, and still photographs of people running or dancing). Neurons that respond

Table 1 | **Types of conjuring effects***

Magic effects	Examples	Methodological strategies
Appearance: an object appears 'as if by magic'	Pulling a rabbit out of a hat; the Miser's Dream (in which hundreds of coins seem to appear where previously there were none)[75,94] (BOX 2; Supplementary information S2 (movie)); Mac King's giant rock in a shoe trick[75,87] (Supplementary information S3 (movie))	• The object was already there but was concealed (for example, the magician might conceal a coin in his or her hand prior to its production) • The object was secretly put into position (for example, in the Cups and Balls routine, various objects are secretly loaded under the cups during the routine) • The object is not there but seems to be (for example, a 'medium' can simulate the presence of a spirit at a séance by secretly touching a spectator)
Vanish: an object disappears 'as if by magic'	Vanishing of a coin; Penn and Teller's underwater vanishing of a naval submarine; David Copperfield's vanishing of the Statue of Liberty	• The object was not really where it appeared to be to begin with (for example, the magician fakes a transfer of a coin from the left hand to the right hand, then shows that the coin 'disappeared' from the right) • The object has been secretly removed (for example, the magician uses a secret device, called a gimmick, to pull an object into his sleeve) • The object is still there but is concealed (a coin can seem to vanish from the magician's hand although in reality it is merely concealed)
Transposition: an object changes position in space from position A to position B	Houdini's Metamorphosis (in which two people change places between locked boxes); Penn and Teller's Hanging Man Trick (in which Penn is apparently hanged to death, only to be found safe and sound in the audience)	• The object seemed to be at A, but actually was already at B (for example, the magician fakes the transfer of a coin from the right to the left hand, then pretends to transfer the coin magically from left to right) • The object is still at A but seems to be at B (for example, the magician fakes a coin transfer from the left hand to the right and then, when revealing the coin by dropping it, uses sleight of hand to give the impression that it was dropped from the right hand) • The object was secretly moved from A to B (for example, a coin in the left hand is secretly transferred to the right hand and then is revealed there) • A duplicate object is used (for example, both hands hold identical coins that are revealed at different times to simulate a transfer)
Restoration: an object is damaged and then restored to its original condition	Cutting and restoring a rope; sawing an assistant in half; tearing and restoring a newspaper; breaking and restoring rubber bands	• The object was not really damaged • The object was not really restored • A duplicate is used
Penetration: matter seems to magically move through matter	Chinese Linking Rings (metal rings that link and unlink magically); Houdini's Walking Through a Wall trick; Coins Through the Table	• Penetrations combine the techniques used in the transposition and restoration categories
Transformation: an object changes form (size, colour, shape, weight, etc.)	Colour-Changing Card Trick; Spellbound (in which a coin turns into a different coin); The Professor's Nightmare (in which three ropes of different length are made equal in length)	Transformations can be seen as the vanishing of object A combined with the appearance of object B: • Object A was secretly switched with object B • Object B was always present but was initially disguised as object A • Object A is disguised as object B at the point of 'transformation'
Extraordinary feats (including mental and physical feats)	Extraordinary memory (remembering the names of all the audience members); extraordinary calculation (reporting the result of multiplying randomly selected 4-digit numbers); extraordinary strength; invulnerability (specific examples: walking on hot coals; Penn and Teller's bullet-catching trick)	• Might rely on relatively obscure scientific knowledge (such as mathematical or physiological knowledge). For example, walking on hot coals is harmless when performed correctly
Telekinesis: 'magical' levitation or animation of an object	Levitation; spoon bending	• The action is caused by an external force (for example, an invisible thread) • The action is caused by an internal force (elasticity, chemical reaction, magnetism, etc.) • The action did not actually occur (for example, a spoon bender can convince a spectator that a stationary spoon is still bending)
Extrasensory perception (ESP; including clairvoyance, telepathy, precognition, mental control, etc.)	Clairvoyance (acquiring information that is not known to others through ESP); telepathy (acquiring information that is known to others through ESP); precognition (acquiring information from the future); mental control (the performer influences the selection process of another person)	• Controlling a spectator's choices to give the illusion of free will • Discovering hidden information (for example, reading information that has been sealed in an envelope, fishing for or pumping information from a spectator, cold reading, etc.) • Revealing apparent proof that information announced by the spectator was previously known by the magician (for example, by writing the announcement on paper and using sleight of hand to make the paper seem to come out of an envelope that was sealed before the announcement)

*We adopt Lamont and Wiseman's classification[7] of conjuring or magic effects into nine main categories.

to implied motion are found in extrastriate visual areas of the dorsal stream, and they are thought to be also sensitive to real motion[54,55]. Thus, implied motion might activate similar circuits to those that are active during the perception of real motion, and this might result in perceptual illusions. Another example of this might be when one pretends to throw a stick for a dog during a game of fetch.

How do magicians misdirect the audience's attentional spotlight? Magicians can effectively control an object's salience by manipulating the audience's bottom-up and/or top-down attentional control mechanisms. Objects that are new, unusual, of high contrast or moving are salient, and the audience's attention is more strongly drawn towards them. Such object properties induce bottom-up control of attention (and are used to accomplish 'passive misdirection' in magic theory[7,56] or 'exogenous attentional capture' in psychology) because the attention is driven by increased activity in the ascending sensory system. One way in which a magician might control bottom-up attention is by suddenly producing a flying dove. The spectators' gaze and attention will focus on the dove's flight, and this will give the magician a few unattended moments in which he or she can conduct a secret manoeuvre.

Another facet of bottom-up attention that magicians exploit is the fact that if more than one movement is visible, spectators will tend to follow the larger (that is, the more salient) motion[7]. Hence the magician's axiom, '*A big move covers a small move.*' A neural process that might underlie this axiom is the low-level mechanism of contrast-gain control (or contrast-gain adaptation)[57]. In contrast-gain control, the perceived contrast of a stimulus is affected by the contrast of surrounding stimuli (whereas in contrast-gain adaptation, the perceived contrast of a stimulus is affected by that of a preceding stimulus)[58]. A large or fast-moving stimulus might therefore decrease the perceived salience of a small or more slowly moving stimulus that is presented either simultaneously (in contrast-gain control) or subsequently (in contrast-gain adaptation). Novel stimuli are known to produce stronger neural responses in the inferotemporal cortex (area IT), the hippocampus, the prefrontal cortex and the lateral intraparietal area[59–63]; these effects are attributed to bottom-up attentional processes.

The salience of an object can also be increased by actively directing attention to it. For example, a magician might ask a subject to perform a task that involves one specific object, so that any changes that are occurring in a second object are missed. Such techniques are considered to induce top-down attentional control (and are used by magicians to accomplish 'active misdirection' (REFS 7,56) or by psychologists to accomplish 'endogenous attentional capture') because they modulate (increase or decrease) neural activity in low-level brain areas through feedback pathways from high-level brain areas that are involved in cognitive functions[64]. One example of top-down attentional modulation is provided by recent work by Chen and colleagues[65], which shows that neural responses in the primary visual cortex, an early visual-processing area, are enhanced as a function of task difficulty during attentional tasks. Another example of top-down attentional control is when a magician asks the audience to watch carefully an object that is being manipulated in one hand, while at the same time conducting a secret action with the other hand.

The principles that underlie attentional capture and contrast-gain control and adaptation also apply to other sensory systems, for example the somatosensory system. Pickpockets use techniques similar to those that are used by magicians (for instance, sleight-of-hand manoeuvres) to manipulate the awareness and attention of their marks. One way in which pickpockets manipulate the somatosensory system by applying the axiom '*A big move covers a small move*' is as follows. To steal a watch directly from the wrist of a mark, the pickpocket might first squeeze the wrist while the watch is still on[66] (invoking contrast-gain adaptation). This has two effects. First, it makes a high-contrast somatosensory impression that adapts the touch receptors in the skin, making them less sensitive to the subsequent light touches that are required to unbuckle and remove the watch. Second, the high-contrast impression leaves behind a somatosensory after-image, giving rise to the illusion that the watch is still on after it has been removed.

Another way in which magicians can alter an object's salience is to split the audience's attention by introducing several concurrent actions[24]. If two actions start almost simultaneously, the one that begins first will usually attract more attention[7,67]. Social cues, such as the magician's gaze (for instance, in the Vanishing-Ball Illusion), their voice and verbal communication and their body language (pointing, tension/relaxation), also play an important part in manipulating the spectator's attentional spotlight[7].

Misdirection occurs not only in space (what the audience looks at) but also in time (when the audience looks). Thus, magicians strive to redirect the audience's attention away from the moment of the method and towards the moment of 'magic'. Indeed, in many magic tricks the secret action occurs when the spectators think that the trick has not yet begun, or when they think that the trick is over. Many magicians use comedy and laughter as a way to reduce focused attention at critical points in time. The magicians' term 'time misdirection' refers to the deliberate separation of the moment of the method from the moment of the effect. Usually a delay is introduced between method (that is, cause) and effect, preventing the spectator from causally linking the two[7].

Memory illusions and illusory correlations. Magic works in adverse circumstances: an important part of the entertainment is that spectators are naturally suspicious and will try to discover the method behind the trick. Thus, observers of a magic trick will often try to reconstruct events to understand what happened. However, a successful magician will either have made it impossible to discover the method, or will seem to have ruled out all possible methods (including the actual method) until magic is the only apparent explanation[7,68] (see Supplementary information S1 (movie)). The magician can also influence the spectators' recall of the performance by using misdirection: events that draw the spectators' attention will be better remembered than less salient events[7,24,69]. An apparently natural or spontaneous action, such as scratching one's head, will not be memorable (although it might be critical to the execution of the trick). Unspoken assumptions and implied information are also important to both the perception of the magic trick and its subsequent reconstruction[7]. J.R. has observed that spectators are more easily lulled into eagerly accepting suggestions and unspoken information than into accepting direct assertions[70] (see Supplementary information S2 (movie)). Thus, in the process of reconstruction, implication can be remembered as direct proof. The magician can further influence future recollection by describing past events in a manner that will bias the reconstruction process[7]. This is known in cognitive science as the 'misinformation effect' — that is, the tendency for misleading information presented after the event to reduce one's memory accuracy for the original event. This effect can even lead to the creation of a 'false memory' for events that never took place[69]. The famous Indian Rope Trick legend might have partially resulted from the misinformation effect. In the Indian Rope Trick, a boy climbs a magically suspended rope and disappears at the top. The magician follows the boy up the rope into the invisible area at the top and cuts him into pieces (evidenced by the bloody body parts falling from the invisible area down to the ground). The magician then descends the rope and magically reintegrates the boy with no harm done. In fact, the Indian Rope Trick has never been performed, despite numerous witness accounts[71–73].

Although the study of false memory and misinformation effects has become a mainstream topic in cognitive science over the past few decades, it is possible that the field would have advanced faster if scientists had looked at the magicians' intuition of human memory earlier. Even today, despite the substantial progress that scientists have already made in this area, the misinformation effect as used by magicians could be robustly reproduced in the laboratory to study the neural underpinnings of memory mechanisms and, in particular, false-memory mechanisms.

Glossary

After-discharge
A sensory neuron's response to the turning off of a stimulus.

Blindsight
A neurological condition in which a patient with damage in the primary visual cortex is unaware of visual events that occur in the corresponding portion of the visual field, despite exhibiting good performance on visual tasks conducted in that region.

Change blindness
The failure to notice changes in an object or scene over a period of time.

Inattentional blindness
The failure to notice a salient object or visible feature in a scene owing to misdirected attention or attention that is not engaged at a level sufficient to achieve awareness of the object.

Magic palming technique
The technique used by magicians to hide items in the palms of their hands (which are turned away from the observer), so as to make it look like the hands are empty.

Microsaccades
Small, involuntary saccades that are produced when subjects attempt to fixate their gaze on a visual target.

Saccade
A fast, jerky eye movement that transports the fovea from one visual target to another in a straight-line trajectory.

Smooth pursuit movement
A type of eye movement in which the retinal fovea smoothly tracks the position of a moving object.

Magicians can also make their audiences incorrectly link cause and effect. We all infer cause and effect in everyday life. When A precedes B, we often conclude that A causes B. The skilled magician takes advantage of this inference by making sure that event A (for example, pouring water on a ball) always precedes event B (in this case, the ball disappearing). However, A does not actually cause B: the magician only makes it seem so[74,75]. This type of illusion — seeing a correlation that is not there — is termed an 'illusory correlation'. Illusory correlations can arise from unequal weighting of information, from the participants' expectancies (such as prior beliefs or stereotypical knowledge) and/or from selective attention and encoding. In this third possibility, illusory correlations arise when some events capture more attention or are more likely to be encoded in memory and remembered than other, less salient, events[76]. Thus, the magician can effectively use misdirection techniques to draw illusory correlations between two unrelated events. Just as visual scientists use visual illusions to identify the neural mechanisms of perception, neuroscientists could use illusory correlations to identify the neural mechanisms that underlie the cognitive computations of cause and effect. In a recent study by Parris and colleagues[77], participants underwent functional MRI (fMRI) while watching films of magic tricks that involved apparent cause–effect violations. The brain activation that was induced by the watching of these films was compared with the activation that occurred in a control condition in which participants watched video clips of events that did not involve apparent causal violations. The results showed greater activation in inferior medial frontal areas during the viewing of magic tricks than during the viewing of the control videos.

The illusion of trust. Pickpockets rely heavily on social misdirection. Gaze contact, body contact[7] and invasion of the mark's personal space[24] are effective misdirection techniques (see Supplementary information S3 (movie)). Further, magicians and professional pickpockets use established techniques of persuasion to manipulate the trust of their audiences/marks. Some of these principles are also used by confidence artists in various scams and frauds. Brain-imaging studies of subjects playing online trust-building games show that activation in the paracingulate cortex is critical to building a trusting relationship. This activation seems to be related to inferring the partner's intentions so as to predict their behaviour[78]. Once trust was established, activity in the ventral tegmental area, which is linked to the evaluation of expected and realized reward, was correlated with the maintenance of 'conditional trust' (REFS 79,80). 'Unconditional trust' was correlated with activity in the septal area, which is linked to social attachment[81–83]. Future research will determine the role of conditional versus unconditional trust in confidence fraud schemes. Neuroscientists can take advantage of the persuasion techniques that are used by magicians and pickpockets to identify the neural circuits that underlie feelings of trust and mistrust.

Magic principles

Various principles of stage magic aim to manipulate attention and awareness. These principles have been identified by magicians and have been refined over the centuries to great effect. The time is now ripe to take them into the laboratory and use them to guide new and more powerful experimental testing and careful quantification. This would elucidate the mechanistic pathways in the brain that allow magic tricks to work and would also generate novel and robust laboratory techniques for studying attention and awareness. A number of magic principles were discussed during the Magic of Consciousness symposium during the 11th Annual Meeting of the Association for the Scientific Study of Consciousness (BOX 2); they are reviewed below.

An action is a motion that has a purpose. During the execution of a magic trick, it is necessary to use unnatural actions. Thus, the magician needs to reduce the audience's suspicion about such actions. One way to do this is to justify unnatural actions so that they seem natural[7]. Teller[74] refers to this principle with the aphorism, "An action is a motion with a purpose."

In everyday life we categorize the motions made by others by interpreting their intentions. If we see somebody pushing their glasses higher on the bridge of their nose, we assume that the glasses needed adjustment, and no further interpretation is made. A good magician makes use of such innocent actions to hide ulterior motions in a process called 'informing the motion'. For instance, magicians with a mute on-stage persona, like Teller, can take advantage of the glasses-pushing action to discreetly hide a small object in their mouth (being mute, they have no lines to garble). A less clever magician might do the same motion (moving the hand over the mouth) without informing it with

Box 2 | **The Magic of Consciousness symposium**

The Magic of Consciousness symposium took place during the 2007 meeting of the Association for the Scientific Study of Consciousness (Las Vegas, Nevada, June 22nd–25th). In this symposium, the five magicians authoring this paper (M.K., J.R., A.R., T. (the photos show T. demonstrating The Miser's Dream at the symposium) and J.T.) shared their insights about how stage-magic techniques might manipulate attention and awareness[75,94]. The audience consisted of cognitive neuroscientists and consciousness researchers, and the symposium was geared towards establishing collaborations between magicians and scientists so that magic tricks could be replicated in the laboratory. See Supplementary information S1–S6 (movies) for symposium footage that shows how attention is manipulated during magic tricks. The photographs of T. were taken by Jane Kalinowsky for The New York Times[94].

a purpose (adjusting one's glasses). Such a motion will be subject to suspicion and scrutiny. In that case, even if the spectators have not seen exactly how the trick works, they might feel that something is amiss. The skilled magician informs every motion with a convincing intention (see Supplementary information S4 (movie)).

Apparent repetition, priming and 'closing all the doors'. In everyday life, by repeatedly observing a process we are able to deduce its workings. Priming is a type of repetition effect in which the presentation of a stimulus that is similar to a target makes subsequent presentations of the target perceptually more salient[84]. Priming is used experimentally, and by the magician, to affect the subject's sensitivity to a later presentation of a particular stimulus. Moreover, repetition can be used to induce sensory illusions, as in the Vanishing-Ball Illusion described earlier. Spectators are more likely to perceive the illusory ball vanishing in mid-flight if an actual ball has been tossed several times first, so that they are primed to know what an actual tossed ball looks like[85]. Thus, priming and repetition can be helpful in inducing some illusory effects. Magicians also use repetition to hide the method behind the trick: when observers see an effect repeated, they naturally assume that each repetition is done by the same method. But the magician can covertly change the method that underlies each apparent repetition of the effect. Indeed, when a good magician repeats an effect, the method is varied in imperceptible ways and in an unpredictable rhythm. That way, each time observers suspect one method is being used, they find their suspicion disproved by the subsequent repetition[74] (see Supplementary information S4 (movie) and S5 (movie)). The magician might even deliberately raise suspicion about a possible method and then show that suspicion to be unfounded[7]. In this way, the magician closes the door on every possible explanation for the trick[68,73,86], until the only remaining possibility is 'magic'. This tactic is referred to as Tamariz's Theory of False Solutions (see Supplementary information S1 (movie)). The use of apparent repetition has the added benefit of confusing the spectators' reconstruction process. Further, the specific weaknesses of each method will cancel each other out[7].

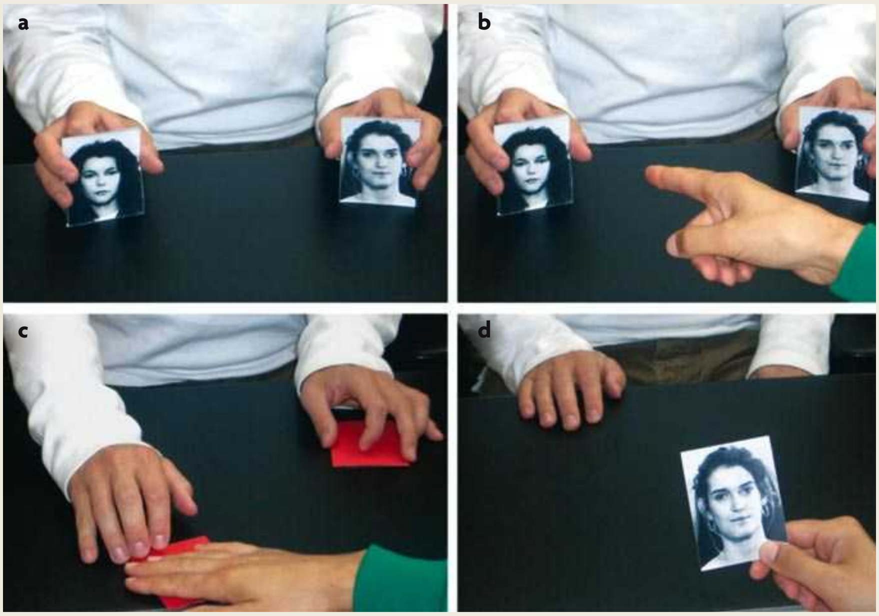
Never do the same trick twice. The corollary of the closing all the doors principle is that if the magician performs the same trick twice for the same audience, there is an increased chance that the audience will identify the method that is being used and figure out the trick[87] (see Supplementary information S5 (movie)). In several studies by Kuhn and colleagues, most observers caught the method when the trick was shown a second time[35,36,40,88]. Similarly, most inattentional-blindness demonstrations are a one-time-only kind of effect. Observers are much more likely to see the gorilla the second time they watch the basketball video described earlier[33].

Conclusions

Magic combines multiple principles of attention, awareness, trust and perception to both overtly and covertly misdirect the audience. Whether they are used for performance art or as a means to illicitly separate victims from their money and valuables, the accomplished performer uses robust and intuitive manipulative devices that are of great interest to neuroscientists pursuing the neural underpinnings of cognition, memory, sensation, social attachment, causal inference and awareness. Among these devices, we would like to emphasize the use of misdirection as a means to generate cognitive illusions such as inattentional blindness, change blindness, memory illusions and illusory correlations. Magicians are able to obtain these effects under conditions of high scrutiny show after show. Some of the crucial principles one needs to take into account when designing a robust trick are the understanding that every motion should seem to have a purpose, that the magician should not perform the same exact trick twice, and that the most successful tricks use apparent repetition to close all the doors on every possible explanation of the trick except for 'magic' itself.

Cognitive neuroscience endeavors to reverse-engineer the entire spectrum of cognition by determining the neural correlates of the various cognitive processes that make up our lives. Magic techniques can provide methods and insights that could help to explain what happens in the brain when a spectator thinks he knows what happened on stage[73]. The possibilities of using magic as a source of cognitive illusions to help isolate the neural circuits that underlie specific cognitive functions are endless. For example, the magicians authoring this article emphasize the use of humour as a critical aid to the successful implementation of many tricks. Their intuition is that when the audience is laughing it is as if time stops and the attentional spotlight is put on hold. That is, the magician can do virtually anything when the audience is laughing, and nobody will notice. Recording neural activity (by fMRI, electroencephalogram, magnetoencephalography, *et cetera*) in someone who is watching magic tricks that are accompanied by humour

Box 3 | **Magic techniques in the choice-blindness paradigm**



Johansson and colleagues[89,90] recently developed an experimental paradigm in which the relationship between a subject's behavioural choice and that choice's outcome is surreptitiously manipulated. Subjects were shown picture pairs of female faces (see figure, part **a**) and were asked to choose which face in each pair they found most attractive (part **b**). On some trials, participants were also asked to describe the reasons behind their choice. Unknown to the subjects, the researchers occasionally switched one face for the other after the subjects had made their choice (part **c**). To perform the switches, the investigators learned sleight-of-hand techniques (a double-card ploy) from a professional magician (Peter Rosengren). During manipulated trials, the result of the subject's choice became the opposite of his or her initial intention (part **d**). Interestingly, only 26% of all manipulated trials were caught by the subjects. Even more surprisingly, when the subjects were asked to state the reasons behind their choice in the manipulated trials, they confabulated to justify the outcome, which was opposite to their actual choice. Johansson and colleagues called this phenomenon "choice blindness". In addition to the important implications of the choice-blindness paradigm for the cognitive sciences, these studies are also pioneers in the incipient dialogue between cognitive neuroscience and magic techniques. Images reproduced, with permission, from REF. 90 © (2005) American Association for the Advancement of Science.

might help researchers determine the potential interaction between the allocation of attention and the sensation of mirth. Further possibilities range far beyond the uses of magic that have already been tried experimentally in cognitive science, such as the employment of magic palming techniques to direct subjects into confabulating their reasons for choices that they did not actually make[89,90] (BOX 3). Magical cognitive illusions are furthermore an outstanding method by which to dissociate the perceived contents of awareness from the actual physical events. That is, one primary purpose of magic is to segregate those events that the magician does not want the observers to be aware of from those that the magician does want them to be aware of. We propose therefore that magical techniques that manipulate attention and awareness can be exploited to directly study the behavioural and neural basis of consciousness itself, for instance through the use of brain imaging and other neural recording techniques. If neuroscience researchers succeed in adopting magical methods with the same alacrity as professional magicians, they too should be able to control sensory awareness precisely and in real-time, while at the same time assessing the neural activation that is associated with it.

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Association for the Scientific Study of Consciousness: http://assc.caltech.edu/index.htm
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