Mind & Society (2005) 4: 27–48
DOI 10.1007/s11299-005-0005-8

ORIGINAL ARTICLE

**Philip N. Johnson-Laird**

# Flying bicycles: How the Wright brothers invented the airplane

Received: 31 May 2004 / Accepted: 28 June 2004

**Abstract** This paper explores the ways in which Wilbur and Orville Wright thought as they tackled the problem of designing and constructing a heavier-than-air craft that would fly under its own power and under their control. It argues that their use of analogy and their use of knowledge in diagnostic reasoning lies outside the scope of current psychological theories and their computer implementations. They used analogies based on mental models of one system, such as the wings, to help them to develop theories of another system, such as the propellers. They were also skilled reasoners, who were adept at finding counterexamples to arguments.

**Keywords** Airplanes · Analogy · Abduction · Deduction · Explanation · Induction · Mental models · Reasoning

## 1 Introduction

When Wilbur and Orville Wright were children, their father gave them a flying toy. It was a simple helicopter-like device powered by a rubber band. Like most children, they were fascinated by the way it flew. But, unlike most children, they were ingenious enough to make copies of the toy on a larger scale. To their disappointment, the larger versions did not fly. They had learned their first lesson in aeronautics: what works on a small scale does not necessarily work on a large scale. The brothers owed their practical know-how to their mother, who was the daughter of a carriage-maker from

P. N. Johnson-Laird (✉)
Department of Psychology, Princeton University, Princeton NJ 08544, USA
E-mail: phil@princeton.edu

Saxony. When she mended a toy, it was better than the original. Their father was quite impractical. He was a bishop in an evangelical sect, the Church of the United Brethren in Christ. He was pious, strong willed, litigious. And he was often away from home on church business. He was strict but loving. Wilbur had been intended for Yale, but a severe skating accident and his ensuing depression ended these plans. Orville had no such ambitions. But, the two boys, played together, worked together, and thought together. Their mother fell mortally ill, and Wilbur was her devoted nurse. After her death, her daughter Katharine, the youngest in the family, took over the running of the household until she went off to Oberlin University in 1893. The brothers were left to fend for themselves and their father, and to run their fledgling bicycle business (for these biographical details, see e.g., Crouch 1989).

Ten years later, they were the first to fly a heavier-than-air craft under its own power and under the pilot's control. Their "flyer" was a machine that they had designed and built, and its motor was an internal combustion engine also of their own design. Their first flights took place just over a hundred years ago from the Kill Devil Hills near Kitty Hawk on the Outer Banks of North Carolina. It had taken them less than five years to invent the airplane. They had made no significant models of the plane, except in their minds, but instead developed its design from a kite and three man-carrying gliders (see e.g., Wright 1988).

Why did they succeed when so many failed? There have been many conjectures, ranging from their exceptional mechanical ability to the psychodynamics of their lives as bachelors unencumbered by any sexual relationships. As with any historical puzzle, we can never know for certain what was crucial. Indeed, one view is that they had no exceptional abilities. A multiplicity of other factors, each insignificant in itself, led in aggregate to their success. This peculiar combination of circumstances might never have occurred again. If time were turned back to the start of their efforts in 1899, and then rerun, it is unlikely that they would have succeeded again. This was Wilbur's view – in almost his very words (see Kelly 1951). He was impressed only by the short time it had taken, but ascribed it to luck rather than to intellect.

Wilbur's view is untenable. What shows that the brothers had exceptional ability is the exceptional lead that they established over their rivals. Long after they had discovered the principles of flight, others were either stealing their ideas or crashing aircraft with fatal regularity. We can eliminate at once a number of potential factors for success – some because the Wrights lacked them, some because their rivals possessed them. The Wrights had no education beyond high school, and no scientific training. They were not rich. Their cycle business enabled them to take time off for their experiments and to pay for their machines – not that their craft were expensive (the flyer cost less than $1,000, they reckoned). They were skillful in making and repairing machines; Orville had already devised a printing press and a calculating machine of his own designs. They were conscientious, stubborn, persistent. Yet, their rivals included trained engineers with skill, persistence, time, and money. Samuel Langley, the secretary of the Smithsonian Institution in Washington, received $150,000 of tax payers' money to build a plane (see Tobin 2003).

Perhaps the Wrights merely had the necessary qualities to a greater degree. It is possible. But a more likely hypothesis is that their lead came from their way of thinking about the problems of flight, and from how they went about solving these problems. They seldom remarked about their methods – they were too busy thinking to have time to reflect on *how* they were thinking, and, in any case, as cognitive psychologists know to their cost, the sources of creativity are mostly unconscious. Thinking seems seamless. But, in fact, a variety of underlying steps can lead from one idea to another. A nebulous association can precede a mechanical calculation. And only the surface of thinking is reflected in the stream of consciousness. Efforts to develop computer models of thinking reveal how much more must be outside awareness. My attempt here to reconstruct their thinking is therefore speculative, but it is based on scattered clues in their writings and recent theorizing in cognitive science.

One other view, of course, is that the Wrights were geniuses and genius is inexplicable. I fancy that they would have been wryly amused by this idea. They were levelheaded practical men from Dayton, Ohio. They had genius of a sort, but the record makes it intelligible.

## 2 The nature of creativity

To create anything is by definition to come up with something new – for you at least, if not for others. But novelty is not enough. Whether you are creating a work of art or a practical invention, you have to meet certain criteria or constraints. An airplane has to fly. The process of creative thinking does not unfold like clockwork: it is not deterministic in this way. Granted this account, there are only three sorts of process that can be creative (see Johnson-Laird 1988). One sort, "neo-Darwinian" creativity, mimics the evolution of species. Like genes, existing concepts are shuffled at random to create new ideas. Like natural selection, criteria based on knowledge and experience allow you to sort out what, if anything, is viable – to which the entire process can be applied again and again until perhaps something useful emerges. Nowadays computer programs simulate this evolution of ideas, and they can approach optimal solutions to certain problems, such as minimizing the length of connections in an integrated circuit (see e.g., Holland et al. 1986). But, the process is grossly inefficient, and evolution works this way only because the experience of an organism cannot be encoded in the genes that it passes on to its offspring (see Mayr 1982). Human creativity is seldom trial and error of this sort, with knowledge acting solely as a sieve. And the Wrights did not work this way.

Some exceptional individuals can create immediate works of art without the need for revision. These artists include musical improvisers such as Ludwig van Beethoven, spontaneous wits such as Oscar Wilde, and extempore dancers such as Isadora Duncan. They use their tacit knowledge to *constrain* the creation of ideas, and it ensures that any choice they make is at least fitting, and sometimes inspired. Such processes benefit from the acquisition of knowledge from experience, and this sort of creativity is "neo-Lamarckian" because it resembles Lamarck's theory of evolution (for an account of how jazz musicians improvise in a neo-Lamarckian way, see Johnson-Laird 2002). No inventor could work in this way. To acquire the necessary knowledge would be to have the invention already in mind. And the Wrights did not work this way, either.

In the third sort of creativity, individuals use some knowledge to constrain their imagination and other knowledge to evaluate its results. They cycle through these creative and critical stages many times. The Wrights worked in this "multi-stage" way. They used some prior constraints in creating their aircraft, but they also tested their ideas in practice to see whether they met other constraints, returning the results for further creative work, re-evaluating these results, and so on and on. Like many original thinkers, they thought hard about what it was that they wanted to invent, and then used these criteria to measure their success.

One reason for the long controversy about who invented the airplane was that other contenders had formulated less stringent criteria for what would count as an airplane. If success were only a matter of getting a heavier-than-air machine aloft, then others such as Sir Hiram Maxim, the inventor of the eponymous machine gun, Samuel Langley of the Smithsonian, or Richard Pearse, the New Zealand pioneer, could be said to have been the first to fly. But, an old flying adage is that a *good* landing is one that the pilot can walk away from, and a *great* landing is one that leaves the machine fit for someone else to fly. There were no good landings, let alone great ones, until the flights at Kitty Hawk a century ago.

A general principle in the Wrights' thinking was to avoid trial and error (neo-Darwinian creativity). To speak in the jargon of contemporary cognitive science, they used constraints to minimize the size of the "problem space" in which they had to search for a solution (cf., Newell and Simon 1972). Their aim was to build aircraft, not to acquire scientific knowledge. In the late nineteenth century, scientists looked askance at aeronautical explorations. The great physicist Lord Kelvin, for instance, wrote in 1898 that efforts in aviation "could only lead to disappointment, if carried out with any expectation of leading to a useful flying machine". The brothers' interest in the principles of flight was accordingly practical. If they could find the knowledge they needed in the literature, then their design would meet the criteria that it set. If they could not find it in the literature, then they would develop it for themselves.

So it was that they began their serious efforts to construct a flying machine in May 1899 when Wilbur wrote to the Smithsonian requesting papers on flying and a list of recommended readings. His immediate inspirations were a recent book on ornithology, and the death a few years earlier of the German pioneer Otto Lilienthal, who had crashed and killed himself in one of his hanggliders. But, why did Wilbur want to invent an airplane? In his letter to the Smithsonian, he explained that he had been interested in mechanical flight since his childhood experiences in constructing flying toys of several sizes. Years later, Orville said that they had also both become enthusiastic about gliding as a sport (see Wright 1988). Yet, this claim hardly measures up to the intensity of Wilbur's motivation. He was, he said, afflicted with the belief that flight was possible, and the disease might cost him his livelihood if not his life. He was confident that he could advance beyond other workers in the field. A quest can be as addictive as an opiate; but how individuals become addicted to aspirations is not known.

## 3 Wilbur's reasoning and the control of aircraft

Wilbur spent three months reading up aeronautical history. As a result, he realized that much of it was half-baked. He also realized that an airplane depends on three components: wings to provide it with lift, an engine to propel it, and a control system to enable to the pilot to guide it. Sir George Cayley, the English glider pioneer of the early nineteenth century, had made the same analysis. But which component was the most important?

Many of the Wrights' contemporaries believed that all that was lacking for success was a light but powerful motor. "Give us a motor," said Sir Hiram Maxim, "and we will very soon give you a successful flying machine" (Jakab 1990, p. 26). Equipped with two such steam engines, however, his behemoth had fluttered briefly from its track in 1894, and crashed. The Wrights put no priority on motors. In an epitome of the airplane's invention, Wilbur wrote, "It is possible to fly without motors, but not without knowledge & skill". With hindsight, the claim is obvious, but consider Wilbur's reasoning. First, he drew a plausible inductive inference: engines fail from time to time, and so an airplane's engine is liable to fail. (An inductive inference goes beyond the information given, and so there is no guarantee that its conclusion is true even if its premises are true.) Next, he found a clear counterexample to the view that an engine would solve the problem. If the engine fails but the pilot has no control of the aircraft, then disaster follows. This claim was a further induction from the fate of Lilienthal and other glider pilots such as the Englishman Percy Pilcher, who had died in the same way as Lilienthal. Both lacked control of their gliders. Finally, Wilbur concluded, with control of an aircraft under all conditions, engine failure is unimportant because the pilot will be able to make a safe landing.

A remarkable feature of Wilbur's thinking is how few aeronautical pioneers reasoned in the same way. They wanted to fly first, and think later. One who put flight ahead of reasoning was John J. Montgomery, the first to fly a glider in the U.S.A. His gliders were designed with little knowledge of the principles of control. One was cut adrift from a balloon at several thousand feet, and, after one or two flights, it went out of control sending its pilot to his death. Montgomery himself died the same way, later. Wilbur knew Montgomery, foresaw catastrophe, but had no way to avert it (see Crouch 1989).

The Wrights were intelligent. But what *is* intelligence? There was a time when psychologists said that it was whatever intelligence tests measure. They know better now. They know that one of its major components is the ability to reason. Individuals who reason well score higher on intelligence tests than those who reason poorly (see Stanovich 1999). The result is unsurprising, but what is striking are the vast differences from one person to another in reasoning ability. In many psychological studies, the differences could hardly be any bigger (see e.g., Johnson-Laird 1983). The orthodox view in psychology used to be that reasoning depends on a formal logical calculus in the brain. Evidence increasingly suggests, however, that it depends, not on such a formal system, but on a grasp of meanings and access to knowledge (see e.g., Johnson-Laird and Byrne 1991, and Johnson-Laird 2001). It calls for us to envisage what is possible given some starting information and our general knowledge. We represent each of these possibilities in a mental model of the situation, and try to find a relation in the set of models not explicitly asserted in the premises. Depending on whether this relation holds in all, most, or some of the possibilities, we formulate a conclusion about its necessary, probable, or possible truth. We can refute a necessary conclusion by finding a counterexample, that is, a mental model of possibility compatible with the starting information but in which the conclusion does not hold. For most of us, reasoning is difficult, because it is hard to hold in mind more than a few models of possibilities (see Johnson-Laird and Byrne 1991). It can also be hard to find counterexamples to refute invalid inferences. The Wrights had no such difficulty. One of Wilbur's few remarks about their mental abilities was: "It is a characteristic of all our family to be able to see the weak points of anything ...". But most of us tend to reach our decisions guided by our feelings, as the English novelist Trollope once remarked, rather than by sustained chains of reasoning (see Oatley and Johnson-Laird 2002).

## 4 Control and the analogy with bicycles

The brothers not only set maneuverability under the pilot's control as the decisive criterion for a successful airplane, but they also differed from other aeronauts on the nature of control. Rivals such as Maxim and Langley aimed for a machine that would fly in a stable equilibrium – in a straight undeviating line that we hope for in a cruising airliner. Cars, coaches, buses, trains, and trucks, move us from one place to another, and they are stable. They may wobble, but they seldom topple. It was natural for inventors to transfer this characteristic to the design of aircraft. They sought stability, for example, in a dihedral configuration of the craft's wings – wings that pointed upwards in a slight V-shape. If a gust of wind rolled the plane to one side, then they supposed that the lower wing would generate more lift than the higher wing and thereby cause a compensatory return to level flight. Still others tried to develop mechanical methods for maintaining stability.

The Wrights eschewed stability. The modern "safety" bicycle with its wheels of equal size was then a quite recent craze. The brothers were keen cyclists, and their business was repairing, selling, and manufacturing bicycles. A bicycle is not a stable vehicle. With practice, however, a rider learns to balance and control it. The brothers inferred by analogy that the essence of equilibrium in an aircraft would be not stability, but control. Like many profound analogies, it concerned not the superficial characteristics of the source of the analogy – the fact, say, that bicycles are made of metal, or that they have two wheels – but instead a complex structure of relations (see Gentner 1983). Riders balance a bicycle, and control it on two axes: turning its front wheel right or left, and leaning it to one side or the other. Pilots should have an analogous control of an aircraft on its three axes. They should control whether it climbs or dives about the horizontal axis from one wingtip to the other, banks to one side or to the other along the horizontal axis from nose to tail, and turns to the right or to the left about its vertical axis.

The analogy has a corollary. Just as cyclists have to learn how to maintain the equilibrium of the machine, so too pilots would have to learn how to control the aircraft. It was crucial, as Wilbur realized, for the brothers to develop expertise in controlling their craft. They would need to have acquired this skill long before they added a motor. Hence, they should begin with gliders.

Analogies were a powerful tool in the Wrights' thinking, and they drew repeatedly on the bicycle as a source. In many ways, their flyer *was* a flying bicycle. Dunbar (1995) has studied scientists' thinking in four leading laboratories of molecular biology. When an experiment failed, the scientists looked for reasons in analogies with other experiments. They drew such analogies at every meeting that Dunbar attended. The Wrights also drew many local analogies between one glider and another. But, the analogy between the control of bicycles and the control of aircraft is altogether deeper. It crosses from one domain to another, though the two domains are members of the same higher category of vehicles. The molecular biologists also used analogies from one domain to another but only when they were thinking about a theory or planning a series of experiments. Gentner (1983) emphasized that such analogies concern, not superficial properties, but complicated matters such as causal relations. Several cognitive scientists have written computer programs that can derive these deep analogies (see e.g., Keane 1988, and Holyoak and Thagard 1989). But, individuals do not always grasp the import of an analogy (see Gick and Holyoak 1983). What is still harder is to find the right analogy among all the knowledge that we possess about the world. The task of comparing a problem to all potentially fruitful analogies is scarcely tractable. The Wrights, as we will see, were in an ideal position to see many analogies between bicycles and aircraft.

## 5 Control and the analogy with birds

The pilots of early gliders, such as Lilienthal, hung from their craft and exercised control by swinging their bodies around to change the center of gravity. With his eye on the goal, Wilbur realized that a powered aircraft would be too heavy to be controlled in this way. A horizontal "rudder", or elevator, could be lifted up or down to control climbing and diving. But, how could banking or turning be controlled?

In the summer of 1899, Wilbur had a key insight from an analogy with birds. He wrote about buzzards: "If the rear edge of the right wing tip is twisted upward and the left downward the bird becomes an animated windmill and instantly begins a turn, a line from its head to its tail being the axis ... In the apparatus I intend to employ I make use of the torsion principle" (McFarland 2001, pp. 15). His idea was to twist the wings of the craft simultaneously in opposite directions so that one presented its leading edge at a greater angle to the oncoming air than the other. As the result of this wing "warping", the two wings would differ in the lift that they generated and so the machine would bank and turn. Here, again, the bicycle reappears. Some early aeronauts had assumed that aircraft would turn on a horizontal plane like automobiles. The brothers realized that the bicycle was a better analogy. To turn, a rider must lean a bicycle, and a pilot must bank an aircraft. Orville, who had by now been co-opted into Wilbur's project, suggested that the outer ends of the wings could pivot on metal shafts, which would be geared to move in opposite directions when the pilot pulled a lever. Such a system is akin to modern ailerons, but metal shafts and gears would have been too heavy for the Wrights' glider.

The next step in Wilbur's thinking is more mysterious. For wings to be warped in opposite directions, they must be flexible. But, if wings are flexible, their ends could flap up and down in ways that would be worse than embarrassing. The solution to this problem came to Wilbur in an analogical insight as he was chatting to a customer in the bicycle shop. He was holding a long thin box for a cycle inner tube in his hands and happened to twist one end of the box in one direction and the other end in the opposite direction. He wrote later, "If you will make a square cardboard tube two inches in diameter and eight or ten long and choose two sides for your planes you will at once see the torsional effect of moving one end of the upper plane forward and the other backward, and how this effect is attained without sacrificing lateral stiffness". The secret was to construct a biplane. Its entire wings could be simultaneously twisted to produce the required warping of the wings without compromising their lateral inflexibility.

Chance favors the prepared mind, as Pasteur is supposed to have said. Wilbur was prepared for his insight, because he had been thinking about how to warp the wings of a plane. When, by chance, he twisted the box, he immediately saw the analogy to a biplane. It depended on visualizing the upper and lower sides of the twisted box as a biplane. Several commentators, notably Jakab, a historian of science, and Ferguson, an engineer, have commented on the Wrights' unusual ability to visualize solutions to their problems (see Jakab 1990 and Ferguson 1992). And Wilbur himself wrote: "My imagination pictures things more vividly than my eyes". It is worth a moment to spell out what underlies this ability.

The computer programs for drawing analogies represent knowledge in a verbal way. To represent, say, the idea that twisting a wing causes it to turn, the programs use representations of the following sort, which I have simplified a little:

(causes (twists wing)(turns wing)).

The only meaning that such words have is that they can match the same words in other data structures that the programs use. So, the use of English words as opposed, say, to numerals is for the convenience of the computer programmer. Verbal representations are plausible if you believe that all thinking is just talking to yourself – a view once popular amongst Behaviorists. The late Richard Feynman was disabused of this error as a schoolboy when a skeptical friend asked him what term he used to describe to himself the crazy shape of a crankshaft (see Feynman 1988, p. 54). And another great physicist, Albert Einstein, wrote: "The words in the language, as they are written, do not seem to play any role in my mechanism of thought. The psychological entities which serve as elements in thought are certain signs and more or less clear images which can be 'voluntarily' reproduced and combined" (Hadamard 1945). Visual imagination is not verbal manipulation.

In a famous study, Shepard and his colleagues showed that individuals can transform objects mentally in ways that are not verbal. In one experiment, itself suggested by a vivid image in one of Shepard's dreams, the participants were presented with pairs of pictures, such as the pair shown in Fig. 1 (Source: Shepard and Metzler 1971).

They had to decide whether each pair of pictures depicted the same object from two different points of view. They reported that they mentally rotated the object in one picture to see whether or not it coincided with the object in the other picture. The two do coincide in Fig. 1. The report was credible because the greater the number of degrees of rotation the longer their judgment took: each sixty degrees of rotation took about one second. This result held for rotations in the picture plane, akin to rotating the picture itself through the required number of degrees. But, it also held for rotations in depth such as the one in Fig. 1, which can be carried out only by representing the three-dimensional object itself and then rotating this representation rather than the two-dimensional image of the picture. The visual system constructs a mental model of the object in the first picture, finds its major axis, and rotates this axis of the object to try to bring the model into alignment with a model of the object in the second picture. What is rotated is therefore, not a two-dimensional image, but a three-dimensional model, such as vision normally produces of the external world (see Marr 1982). Likewise, the analogy between twisting the box and warping the wings depends on a model. The visual system constructs a model of the box. This model serves as the source of the analogy, and the upper and lower surfaces of the box are mapped onto a mental model of a biplane. You "see" the upper and lower surfaces of the box as wings. No current computer program using analogies can carry out this process.

The brothers made a real model of the wings out of bamboo and tissue paper. The design seemed feasible, and so they set to work in July 1899 to

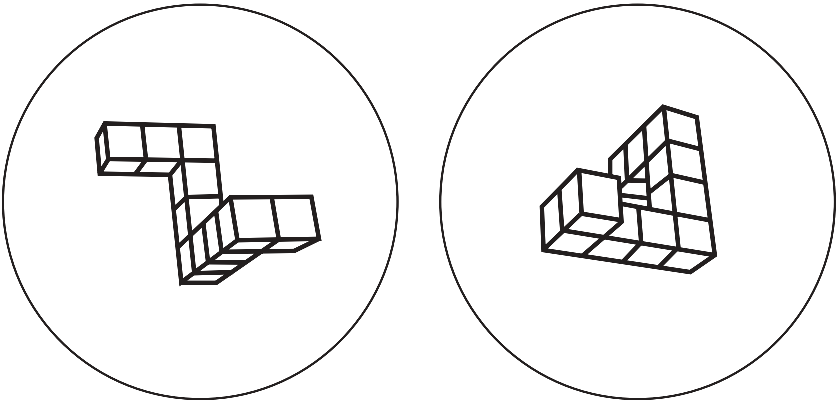

**Fig. 1** Do these two pictures represent the same object? *Source:* Shepard RN, Metzler J (1971) Mental rotation of three-dimensional objects. Science 171: 701–703

construct a biplane kite of the same design with a wingspan of five feet. The operator controlled the kite with a stick in each hand from which two lengths of cord ran, one to the top wing and the other to the bottom wing, so that the ends of the wings could be separately twisted. Wilbur tested the kite and confirmed that wing warping worked. It banked the kite from one side to the other in just the way that he had envisaged.

The Wrights conceived a man-carrying glider on the same principles, and turned to the design of its wings. The wings of an aircraft produce lift: the air travels at the same velocity both over and under the wing. It takes a longer route over the top of the cambered surface of the wing than under the wing, and so the air pressure is less above the wing than under it. This difference lifts the wing. Of course, there is more to the story, because planes can fly upside down: what also matters is the angle of the wing to the oncoming air. The wing also resists the passage of air, as does the body of the aircraft. This resistance is known as *drag* – or drift, as the brothers referred to it. Every wing passing through the air produces both lift, the force at right angles to the flow of air, and drag, the force pushing the wing backwards and therefore in the same direction as the flow of air. The amounts of these forces vary depending on the cross-sectional shape of the wing and its angle to the air. Lilienthal had published a table of these data for his glider's wing, and the brothers used this table in the design of a glider to lift a man aloft in a moderate wind. It was a biplane with a horizontal "rudder" sticking out in front that the pilot could flex up or down to control climbing and diving. At the end of September, the brothers turned their minds back to their bicycle business for the fall and spring.

## 6 Informal inferences in Wilbur's reasoning

Gliders were usually flown from the crest of a hill so that gravity accelerated the craft through the air. Wilbur knew that the procedure was dangerous because the craft was soon high above the ground, which rapidly fell away from the crest of the hill. Lilienthal had died from such a fall. But, was a launch from the top of a hill the only method to get a glider into the air? Wilbur reasoned in the following way in order to come up with a novel solution to the problem. To glide, the air had to move rapidly over the wing in order to produce lift. Hence, Wilbur reasoned, there were two possibilities: the glider could speed through the air, or else the air could speed past the glider. The first possibility could rely on gravity, but that was dangerous. It would be better to use a catapult to launch the glider through the air. That would be safer, but it presented considerable technical difficulties. The second possibility was to speed the air past the glider. That would also be safer, because the glider could stay closer to the ground, and perhaps it could also be tethered to a tower with a counterweight to break its fall. But, how could air be speeded past the wings? The answer was to find a locale that had prevailing winds of a high velocity. This chain of reasoning is a typical example of the informal inferences at which Wilbur excelled. It is not a formal or logical process, but uses relevant knowledge to reach novel conclusions. Psychologists, as yet, have no comprehensive theory of the process, but it may be feasible to extend the mental model theory to explain it (see e.g., Johnson-Laird et al. 2004).

In May 1900, Wilbur wrote the first of many letters to the elder statesman of biplane gliding, Octave Chanute, to outline these ideas and to ask for advice about a suitable locale for glider fights. He also consulted the National Weather Bureau's official tables of average wind speeds at different places. He chose Kitty Hawk on the Outer Banks of North Carolina, a long isolated strip of beach off the coast, lying between a sound and the ocean. The prevailing winds averaged from fifteen to twenty miles per hour.

In August, the brothers began the construction of their first man-carrying glider. The next month Wilbur arrived in Kitty Hawk after a long journey from Dayton, including a perilous sea trip across the sound in a rotting schooner. He had bought the spars for the glider's wings locally, and the longest he could get were two feet shorter than their specification in the design. The rest of the parts arrived, as did Orville, and the brothers assembled the glider, adjusting the fabric to match the shorter spars. In October, they flew the glider, first as a kite, then with Wilbur as a pilot of a tethered glider, and finally with Wilbur as a pilot in free flights. He lay on its lower wing to operate the controls. It looked dangerous, but the brothers soon discovered that it was safe. It had the great advantage of reducing drag in comparison with a pilot sitting upright. Wilbur spent a total time of about two minutes in free flight. It was vital, he believed, for inventors to learn how to fly their craft as they developed them (without killing themselves). For a long time, he was the sole pilot. And, for safety's sake, the brothers flew together only once, many years later after Orville had taken their father for his first flight in a powered flyer.

Two minutes flying was not enough practice, but they had been exciting. According to Lilienthal's table, the glider should have lifted Wilbur in a wind of just over twenty miles an hour with the wings at an angle to the wind of about three degrees. In fact, the wind had to be over twenty-five miles an hour and the wings at an angle of nearly twenty degrees. From his knowledge of aeronautics, Wilbur deduced that there were two possibilities that could account for the poor lift: the fact that the brothers had used a less cambered crosssection than Lilienthal's wing, or that they used smaller wings than those in their original design. Towards the end of October, they left the glider in Kitty Hawk to be cannibalized by the locals – the sateen fabric was used for dresses for two young girls – and they returned to Dayton, where their bicycle business preoccupied them until the next year.

## 7 Problem solving and the center of air pressure

By the middle of May 1901, the brothers had designed their second glider, which took into account the prevailing winds at Kitty Hawk. With a wingspan of 22 feet, it was the largest glider that had ever been built. They gambled by making two untested changes to the wings. They introduced a blunt leading edge, and they reverted to Lilienthal's camber. They employed a friend to look after the bicycle business, and left for Kitty Hawk in early July. There they fought the mosquitoes and built a hangar for the new glider.

They assembled it, and Wilbur made the first flights before the end of the month.

The glider was a big disappointment. It flew erratically, its lift was only a third of the predicted amount, and it was difficult to control. It often dipped into the ground or else, when Wilbur tried to correct the dip, it stalled. A stall occurs when the angle of an aircraft's wings to the airflow becomes too great, turbulence sets in above them, they lose all lift, and the craft takes on the flight characteristics of a real bicycle. Unlike almost all modern planes, the Wrights' aircraft had a design in which the elevator – the horizontal rudder controlling climbing and diving – stuck out in front of the wings like a duck's neck. This configuration is known appropriately in French as the "canard" design. It is illustrated in Fig. 2, which is based on the drawing that the Wrights submitted with their 1903 patent application for wing warping. The brothers later used this same configuration for their powered craft. They discovered that it had an unforeseen advantage. When a craft stalled, it did not make a lethal nosedive into the ground like Lilienthal's glider but dropped flat like a parachute. The canard saved their lives several times.

At the core of the second glider's problems was the difficulty of controlling the center of air pressure, around which all the other air pressures are equally distributed. For perfect equilibrium, the center of air pressure needs to coincide with an aircraft's center of gravity. But, as Wilbur said, the two had "an almost boundless incompatibility of temper which prevents their remaining peaceably together for a single instant, so that the operator, who in this case acts as a peacemaker, often suffers injury to himself while attempting to bring them together". The design of the wings, they thought, should have minimized these problems, but perhaps it had been a mistake to revert to Lilienthal's camber.

The Wrights stopped flying the glider to check what was happening to the center of air pressure. But, how? You might pause for a moment to think what you would do (and to measure your mechanical ingenuity against the brothers'). The problem is to determine how the air is flowing over the glider's wings, and where the center of air pressure is in relation to the wings' center of gravity, when all you have are a few rudimentary tools and

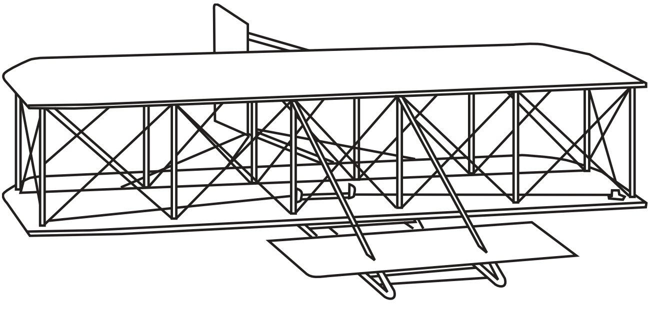

**Fig. 2** A diagram based on the Wright's patent application of 1903. It shows the generic design of their craft with the horizontal elevator in front and the vertical rudder at the back

materials, you are miles from anywhere, and the wind is blowing ceaselessly. Noone to whom I have put this question has so far come up with the Wright's solution.

What they did was to dismantle the glider, and to fly the upper wing as a kite using two cords attached to its leading edge. In a light wind, the wing angled up and pulled the cords up nearly vertically from their hands: the center of pressure had moved in front of the wing's center of gravity, pushing up the front edge of the wing. In a fresher wind, the wing's angle to the wind was smaller and the cords streamed out nearly horizontally from their hands to the wing's leading edge: the center of pressure coincided with the center of gravity, and the wing was in equilibrium. In a still stronger wind, the front of the wing dipped and pulled the cords down from their hands to the leading edge of the wing: the center of pressure had moved behind the center of gravity, pushing the rear of the wing upwards. It was indeed the movement of the center of pressure towards the rear of the wing that would suddenly push their glider downwards, and the deep camber of Lilienthal's design had exacerbated the problem.

The brothers retrussed the wings to change the camber to a shallower one, and they made a sharper leading edge. The modifications solved the problem of control. Wilbur could now skim along over the ground using the elevator to follow its undulations.

For the first time with this glider, they tried wing warping to control banking. It did not work properly. When Wilbur warped the biplanes' wings to bank to the left, the wings on the right came up and the wings on the left went down. But, the maneuver was followed by a bizarre phenomenon. The downward wings now moved through the air faster than the upward wings, and so the craft slewed round to the right even though it was banked to the left. This phenomenon upset both the plane and the brothers' theory of wing warping.

They returned to Dayton dispirited. The lift of the glider was far too low; wing warping had failed. Wilbur is supposed to have said on the train going home: "Not within a thousand years would man ever fly".

## 8 Reasoning and the resolution of inconsistencies

When the brothers encountered a discrepancy between the consequences of their beliefs and incontrovertible evidence, they had to reason back from the inconsistency to a consistent explanation of what was going on. Logic could not tell them which belief they should abandon. And it could not help them to create an explanation that resolved the inconsistency and led on to a cure. In general, when individuals detect an inconsistency between the implications of their beliefs – a task that can be quite difficult (see Johnson-Laird et al. 2000), they need to revise their beliefs. More importantly, they need to create an explanation that resolves the inconsistency. This ability transcends the revision of beliefs. To revert to the Wrights' problem, when their glider failed to produce the predicted lift, they did not merely infer that one of their premises was false. They tried to envisage what had gone wrong. We all have some ability to create such diagnostic explanations. This skill, which some philosophers (e.g., Peirce 1903) refer to as abduction, seems unremarkable, but no existing computer program comes close to matching human ability. Abduction is a species of induction in that its results may be false even if its premises are true, but it goes beyond mere generalization into the domain of causality. For example, you might explain the glider's performance on the assumption that the camber of the wings was wrong, and so the difference in air pressure above and below the wing was not great enough In terms of what is computed in abduction, my colleagues and I have made two principal claims. First, causal explanations can be decomposed into models of temporally-ordered possibilities. Second, individuals use their general knowledge of such possibilities to *construct* a causal chain that explains the inconsistent fact (see Johnson-Laird et al. 2004). Wilbur was adept at such reasoning. He inferred three possible causes for the poor lift: the brothers had changed the wings to a shallow camber; the fabric on the wings may not have been airtight enough; Lilienthal's table that predicted the lift may have been wrong.

## 9 The Wrights' ability to envisage mechanical solutions

In September 1901 at Chanute's invitation, Wilbur gave his first public talk. He was the brothers' official spokesman and for many years their designated writer; Orville never spoke in public in his life. Wilbur's talk was on "Some aeronautical experiments" and he gave it to the Western Society of Engineers in Chicago. Its preparation led him to ruminate on the problem of lift. The brothers needed some way to check Lilienthal's table, which he had based on measurements using a whirling arm with a small section of wing on one end and a counterweight on the other end. But, the method was unreliable.

The brothers' next step depended on their ability to imagine a mechanical device that would yield the answer to a theoretical puzzle. They did away with gravity as the countervailing force. They imagined instead a small flat vertical surface facing directly into the wind. It would produce no lift whatsoever, but pure resistance or drag. It would be their countervailing force, and they would balance it against a vertical cambered wing presented edge on at various angles to the wind. Lilienthal's table would predict the angle to the wind at which the lift (and drag) created by the wing should exactly balance the drag created by the flat plate. They mounted the flat plate and the wing sticking up vertically from the rim of a horizontal bicycle wheel and separated by a quarter of the wheel's circumference. If the wind was constant, then the device would answer: when the forces balanced, the wheel would be stationary; when the forces did not balance, it would rotate. Alas, the winds in Dayton were not constant. So they mounted the wheel horizontally on an axle in front of the handlebars of a bicycle, and surprised the citizens by pedaling the contraption about the town at uniform speed, both into the wind and against it. The wing's angle to the wind had to be much greater than Lilienthal's prediction in order to balance the flat plate. His table seemed to be wrong, but their bicycle may have been no more reliable than his whirling wing.

They constructed a small wind tunnel, and then a larger one, taking a month to ensure that the air flowed in a constant and uniform direction.

Within the wind tunnel, they inserted a new balance system that again compared a wing with a flat surface. A single flat surface created too much turbulence, and so they used instead four narrow strips. The wing was mounted above these strips, and connected to them by a system of bicycle spokes so that the wing's lift (and drag) could be balanced against the drag of the strips. After each initial reading, they readjusted the balance to correct for the wing's drag, and measured its lift alone. A second balance measured the ratio of lift to drag, and so they could also calculate the wing's drag.

Wind tunnels are no longer used in aircraft design. Instead, advanced computer programs accurately model the flow of air over the surfaces of an airplane. The Wrights had an analogous ability to use a mental model to make a rough simulation of the flow of air over surfaces. This ability was sufficient for them to construct wind tunnel balances that yielded accurate measures from which they could compute lift and drag. In the last months of 1901, they ran a series of systematic tests of different cross-sectional wing shapes at varying angles to the air flow. Their observations showed at last that Lilienthal's table was wrong. They also discovered that a long thin wing yielded more lift than a short wide wing of the same area. Others had built wind tunnels before, but they were the first to use them to make accurate measurements. When the time they had allotted came to an end, they stopped these experiments to Chanute's dismay, and returned to their business.

In 1902, the brothers designed their third glider, bearing in mind the wind-tunnel results. They had to correct the problem with wing warping. It banked the glider to one side, but then the downward wings overtook the upward wings and the craft slewed round in the wrong direction. They needed a way to decelerate the downward wings. Once again, they envisaged the flow of air over their glider. Some surface on the plane would have to act as an air break on whichever side was lower when the plane banked. They imagined two fixed vertical tails behind the wings. As the glider banked to one side, the tails would tip into the wind to impede the downward wings.

In late August, they traveled once more to Kitty Hawk. They assembled the new glider, and tested it, as usual, as a kite and then in short glides. On their first trip to the area, Wilbur had kept a notebook in which he recorded his observations of birds. He noted, for example, that the buzzard with its wings in a dihedral angle had greater difficulty in maintaining equilibrium in strong winds than eagles and hawks that hold their wings level. The dihedral angle increased the disturbance produced by side gusts. The brothers had trussed their first glider with a dihedral angle, and found it unsatisfactory. They retrussed the wings on their current glider so that both drooped slightly at the ends to make them less susceptible to side gusts – a feature more appropriate to the strong winds of Kitty Hawk than elsewhere. For the first time, Orville began to pilot the glider. He crashed, damaging the craft but not himself. After repairs, they flew again, and outdistanced the previous year's glides. Yet, the wing warping still did not work properly, and sometimes the fixed tails led to a new problem. The glider was no longer pirouetting around its upward wings, but instead side-slipping in the direction of the downward wings until it started to rotate around them and gouge into the sand like a drill. The brothers had discovered a new danger in flying – the tail spin.

The fixed tails were too effective. The downward wings now moved too slowly, and so they had less lift than the upward wings. Their speed was further reduced, and so on... until the machine spun into the sand as though it were digging a well. They tried removing one of the tails. It made little difference. After a sleepless night, Orville hit on a solution: if the pilot could *control* the vertical tails, then he could turn them to relieve the pressure on their lower sides. He could balance the lift of the upward and downward wings, and thereby steer the craft out of the spin. As they were converting the fixed vanes into a steerable rudder, they had the further idea of connecting the wires that controlled them to those that operated the wing warping. In this way, whenever the pilot warped the wings, the rudder would turn so as to increase the pressure on the same side as the wings with the smaller angle to the wind.

The solution worked. They could glide for over 500 feet with excellent command of the craft. They could bank and turn. They could fly with the wind coming from the side. And they could land safely. They had finally established a full system of control for aircraft: the forward elevator controlled climbing and diving, and wing-warping and the vertical rudders controlled banking and turning. In late October, after much practice in gliding, they returned exhilarated to Dayton. Before the year ended, they applied for a patent for their aircraft and its system of control.

## 10 Analogy and the design of a propeller

The Wrights' had assumed that marine engineers had solved their theoretical problems of designing propellers. Not at all. After over a hundred years of work, no theory of ships' propellers existed. They were designed empirically. So, what should the theory be? They wrote in their article, *The Wright Brothers' Aeroplane* (see Wright 1988):

> What at first seemed a simple problem became more complex the longer we studied it. With the machine moving forward, the air flying backward, the propellers turning sideways, and nothing standing still, it seemed impossible to find a starting-point from which to trace the various simultaneous reactions. Contemplation of it was confusing. After long arguments, we often found ourselves in the ludicrous position of each having been converted to the other's side, with no more agreement than when the discussion began.

The brothers developed a theory. A propeller moves a ship by displacing a volume of water. It bites into the water like a corkscrew moving into a cork as it rotates. And many of the Wrights' predecessors (and successors) supposed that an airplane's propeller should be a flat blade that would cut into the air. But, unlike water, air is highly compressible. Perhaps a propeller should not be flat.

The brothers drew a brilliant analogy with another part of an aircraft. A propeller is a *wing* traveling in a spiral course. The analogy depends on envisaging a model of a wing, carrying out a mental rotation, and observing that it corresponds to half of a rotating propeller. As the wing rotates, it generates, not lift, but *thrust*. A flat blade, like those on Maxim's or Langley's propellers, does not generate much thrust. The blade should instead be cambered like a wing, and the principles for lift apply to the thrust of propellers too.

They designed a propeller for their flyer. It was much more efficient than anyone else's in converting energy into thrust. And their theory predicted its thrust to within one per cent. They were far ahead of their rivals, who continued to use trial and error in their propeller designs. After the brothers had made and tested a prototype, they constructed two wooden propellers. They would use both of them, rotating in opposite directions to balance torque, and mount them behind the wings of the flyer to minimize turbulence.

## 11 Calculation and the engine

The Wrights' rivals sought the lightest and most powerful engines they could get. Langley's engine, for example, was a marvel of economy. It delivered nearly 55 horsepower, and weighed just over 200 pounds. The Wrights in one of their marathon series of calculations worked out the bare minimum that they could get away with. They estimated the area of the powered flyer's wings (500 square feet), and its total weight (625 pounds) complete with engine (200 pounds) and pilot (140–5 pounds). They then calculated the minimum velocity that would lift the machine into the air (23 miles per hour). From this velocity, they calculated the total drag of the wings and the frontal area of the machine (90 pounds). Hence, the engine needed to produce 90 pounds of thrust. And, finally, from the velocity and drag, they calculated that the engine needed to have eight horsepower. They wrote to various manufacturers of internal combustion engines to supply them with a 180 pound engine that would generate eight to nine horsepower.

No commercial manufacturer could meet the Wrights' specification for an engine at a reasonable cost, and so they designed their own. Charlie Taylor, who was a skilled machinist working for them, built it in their cycle workshop. The fuel was gravity fed; it was vaporized in a steel can through which air passed; ignition was by way of make-and-break contacts driven by cams; and the four cylinders were water-cooled. They tested the engine, but the next day the crankcase fractured. By April 1903, they had made a new engine. It weighed less than 180 pounds, and delivered just under twelve horsepower, more than the minimum. Taylor was the only person apart from the brothers themselves, who made a significant contribution to the design and building of the flyer. The brothers never forgot him. When he died in 1958, his only income was social security and an annuity left to him by Orville.

## 12 Simulation and mechanical thinking

The brothers had an engine and two propellers, but how could they connect them? It was no easy matter, Orville wrote, to transmit power from one motor to two propellers rotating in opposite directions. Consider the simple mechanical system illustrated in Fig. 3.

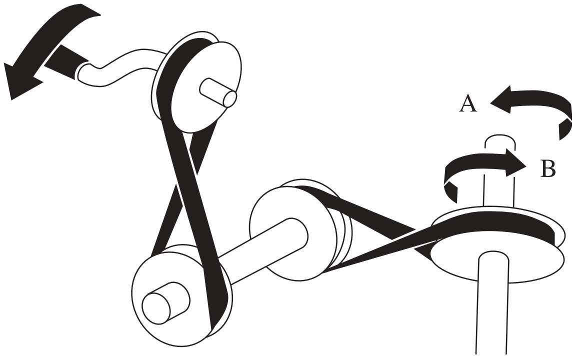

**Fig. 3** A diagram of a simple mechanical problem. *Source:* Hegarty M (1992) Mental animation: Inferring motion from static diagrams of mechanical systems. J Ex Psychol Learning, Memory and Cognition 18(5): 1084–1102

If the handle on the left is turned in the direction shown, then in which direction does the axle on the right move, A or B? Hegarty (1992) has shown that when individuals have to solve such a problem, they first animate one part (the handle), work out the consequences for the next part (the pulley on the same shaft as the handle), work out the further consequences for the next part, and so on, until they arrive at the solution, or lose track of the rotation. The underlying three-dimensional model of the system is mentally animated in a kinematic way, part by part. A super-intelligent being would animate the entire device simultaneously. The great electrical engineer Nikola Tesla was said to have this ability and to use it to envisage which bearing on one of his dynamos would wear out first. Most of us, however, can move our mental models only piecemeal. As Hegarty and Sims have also shown (1994), individuals do differ in their animating ability. The Wrights were experts; and the reader should be able to guess the source of their design for the transmission. Once again, they drew upon the bicycle as an analogy. They used an arrangement of sprockets and chains to transmit the rotation of the engine's shaft to the two propeller shafts. To ensure that one propeller rotated in the opposite direction to the other, they twisted its chain once, like the belts in Fig. 3.

By midsummer, they had completed the transmission, and were busy making the flyer's parts. It was in the familiar canard configuration, but on a larger scale with a wingspan of just over 40 feet. The machine exceeded its estimated weight, but they calculated that the wings should just about lift it into the air under the power of the engine.

## 13 First flights

In late September 1903, they left for their fourth trip to Kitty Hawk with their fourth machine, the powered flyer. The next month they honed their flying skills, practicing on the glider that they had left behind the previous year. They had news of a rival's attempted flight. Langley had had constructed his aircraft, the *Great Aerodrome*. It dived into the Potomac river on its maiden flight – an outcome that would not have surprised the Wrights had they known that Langley had neglected control, and merely scaled up a model aircraft to a large enough size to carry a man. Their flyer was ready, but a trial of the engine damaged the propellers' shafts. The weather became bitter with howling gales and snow. In new trials of the engine, one of the repaired shafts developed a hairline fracture. Orville went back to Dayton, and returned with new shafts made from solid steel and the latest news of Langley's aerodrome. On its second flight, it broke up in midair and fell again into the Potomac. The pilot barely escaped drowning.

The weather turned fairer. With help from the locals, the brothers moved the flyer to its launch site, where a rail was laid out for it to run on. Wilbur won the toss, and so he was to make the first attempt. They started the engine, and, after an initial problem in releasing the restraining wire, the flyer ran down the rail. Before it had come to the end of the rail's final section, it was moving faster than Orville could run. Wilbur pulled the plane up, but too steeply. It reached a height of about fifteen feet, but then stalled, settling hard on the ground and damaging the skids and some struts. They soon repaired it. But the weather delayed them for a couple of days. On Thursday, December 17th 1903, they woke to winds of thirty miles an hour. It seemed to be their last chance for the year, and so they laid out the launching track again. Four locals turned up to help them move the flyer out from the hangar. They started the engine. It was Orville's turn to fly first. On his signal at about 10.35 a.m., the flyer ran down the track with Wilbur at the tip of the right wing. Figure 4 is the famous photograph of the flyer just after take off. It rose into the air and flew for twelve seconds under Orville's control at a speed of around thirty miles per hour. It covered a distance of 120 feet over the ground, and landed at a position no lower than its point of take off. The first true airplane had flown.

Three other flights followed the same day. In the longest, Wilbur flew for 59 seconds. In subsequent years, the brothers made many improvements to the design of their flyers, and they separated the controls of the rudder and of wing warping. There was a hiatus of several years in which they made no flights whilst they tried to sell their machines first to the US War Department, and then, when they were snubbed, to European governments. Their rivals did not catch up. Wilbur took a flyer to France and astounded the French aeronauts, who had deluded themselves that they were leading the race to flight. Orville, at last, demonstrated a flyer to the US military. During the trials, a propeller fractured, and he crashed killing his passenger – the first fatality in an airplane. Their patent was good, but they found themselves in extensive litigation to enforce their rights – an eerie parallel to their father's litigation with rivals in his church. They won every case; but Wilbur was worn out. He died of typhoid on May 30th 1912. His father's brief obituary for him is unsurpassed. He wrote in his diary: "This morning at 3.15, Wilbur passed away, aged 45 years, 1 month and 14 days. A short life, full of consequences. An unfailing intellect, imperturbable temper, great selfreliance, and as great modesty, seeing the right clearly, pursuing it steadily, he lived and died".

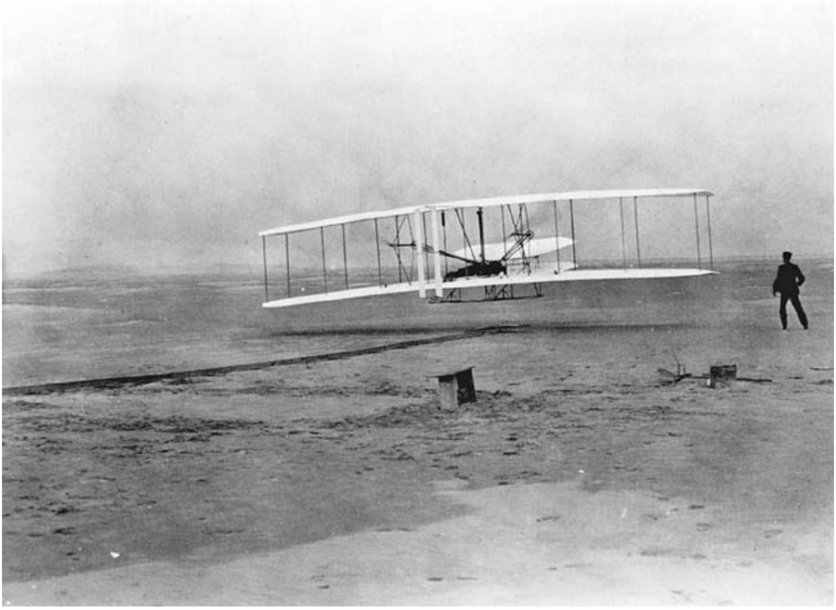

**Fig. 4** The flyer just after take off on its first flight, December 17th 1903. Orville is lying on the wing at the controls; Wilbur is to the right of the machine. *Photo:* Wright Brothers Aeroplane Company-http://www.first-to-fly.com

Orville lived on. He bought out all but one of his partners in the nascent company, and sold it. He was rich, and he retired to his mansion to play practical jokes on friends and relations, and to tinker in his workshop. He invented the split flap, which is still used by planes as they land. He saw nearly all the major developments in aircraft – the jet engine, the helicopter (at which Wilbur had scoffed), the fighter plane, and the bomber. One development that he did not live to see would have pleased him mightily. It was the *Gossamer Condor* – an ultralight aircraft designed by Paul MacCready. Its propeller was driven, not by an engine, but by a very fit cyclist pedaling prone in the streamlined cockpit. A later version flew the English channel.

## 14 Conclusions

Soon after the Wrights had begun their work, they realized that flight was not a single puzzle that trial and error could solve. It called for systematic thought about many problems. "Isn't it astonishing", Orville wrote, "that all these secrets have been preserved for so many years just so that we could discover them". Why did they succeed in flying when so many others failed? They had some luck, great perseverance, skill with their hands, but above all, as I have tried to show, an exceptional ability in thinking. They flew before any of their rivals because they were able to think better than any of their rivals.

Sometimes a step in thought depends on a verbal or numerical representation. But the Wrights had a genius for visualization. It should not be confused with the mere formation of visual images. It depends on the ability to construct mental models of three-dimensional entities or of more abstract structures. They could animate such representations to work out the flow of wind over an aircraft, or to design a transmission system. They could use models in imaginative play constrained by their knowledge to come up with a novel way to truss wings. They could manipulate models in their reasoning to check the consequences of an assumption, to derive a counterexample to a claim, to find a set of possible explanations for inferior performance, or to diagnose a malfunction. And they were most adroit in using a model of one thing, such as bicycle, as an analogy for another, such as an aircraft.

Not long before his death in 1948, Orville was asked whether he regretted his part in the invention of an instrument of death and destruction. In one last apposite Promethean analogy, he replied that he felt about it as he felt about fire: “I regret all the terrible damage caused by fire. But I think it good for the human race that someone discovered how to start fires and that it is possible to put fire to thousands of important uses”.

**Acknowledgements** This research was supported by grant (BCS–0076287) from the National Science Foundation (of the USA) to study strategies in reasoning. I thank my brother Andy Johnson-Laird – an intrepid pilot – for his advice on flying and for a critical reading of this paper, and Nancy Nersessian for her criticisms of an earlier draft.

## References

Crouch TD (1989) The Bishop’s boys: A life of Wilbur and Orville Wright. W.W. Norton, New York

Dunbar K (1995) How scientists really reason: Scientific reasoning in real-world laboratories. In: Sternberg RJ, Davidson J (eds) The nature of insight. The MIT Press, Cambridge, MA, pp 365–395

Ferguson ES (1992) Engineering and the mind’s eye. The MIT Press, Cambridge, MA

Feynman RP (1988) What do you care what other people think?. Norton, New York

Gentner D (1983) Structure mapping: A theoretical framework for analogy. Cogn Sci 7: 155–170

Gick M, Holyoak K (1983) Schema induction and analogical transfer. Cogn Psychol 15: 1–38

Hadamard J (1945) The psychology of invention in the mathematical field, 2nd ed. Published (1996) The mathematician’s mind. Princeton University Press, Princeton

Hegarty M (1992) Mental animation: Inferring motion from static diagrams of mechanical systems. J Exp Psychol Learn 18(5): 1084–1102

Hegarty M, Sims VK (1994) Individual differences in mental animation during mechanical reasoning. Mem Cognition 22: 411–430

Holland JH, Holyoak KJ, Nisbett RE, Thagard P (1986) Induction: Processes of inference, learning, and discovery. The MIT Press, Cambridge, MA

Holyoak KJ, Thagard P (1989) Analogical mapping by constraint satisfaction. Cogn Sci 13: 295–355

Jakab PL (1990) Visions of a flying machine: The Wright brothers and the process of invention. Smithsonian Institution Press, Washington, DC

Johnson-Laird PN (1983) Mental models. Cambridge University Press, Cambridge, and Harvard University Press, Cambridge, MA

Johnson-Laird PN (1988) The computer and the mind: An introduction to cognitive science (2nd ed, 1993). Harvard University Press, Cambridge, MA, and Fontana, London

Johnson-Laird PN (2001) Mental models and deduction. Trends Cogn Sci 5:434–442

Johnson-Laird PN (2002) How jazz musicians improvise. Music Percept 19:415–442

Johnson-Laird PN, Byrne RMJ (1991) Deduction. Lawrence Erlbaum Associates, Hillsdale, NJ

Johnson-Laird PN, Legrenzi P, Girotto V, Legrenzi MS (2000) Illusions in reasoning about consistency. Science 288: 531–532

Johnson-Laird PN, Girotto V, Legrenzi P (2004) Reasoning from inconsistency to consistency. Psychol Rev 111: 640–661

Keane MT (1988) Analogical problem solving. Ellis Horwood, West Sussex

Kelly FC (ed) (1951) Miracle at Kitty Hawk: The letters of Wilbur and Orville. Farrar, Straus, & Young, New York

Marr D (1982) Vision: A computational investigation into the human representation and processing of visual information. W.H. Freeman, San Francisco

Mayr E (1982) The growth of biological thought: Diversity, evolution, and inheritance. Belknap, Harvard University Press, Cambridge, MA

McFarland MW (ed) (2001) The papers of Wilbur and Orville Wright, 2 vols. McGraw-Hill, New York (1st ed, 1953)

Newell A, Simon HA (1972) Human problem solving. PrenticeHall, Englewood Cliffs

Oatley KJ, Johnson-Laird PN (2002) Emotion and reasoning to consistency. In: Moore S, Oaksford M (eds) Emotional cognition: From brain to behavior. Oxford University Press, Oxford, pp 157–182

Peirce CS (1903) Abduction and induction. In: Buchler J (ed) Philosophical writings of Peirce. Dover, New York

Shepard RN, Metzler J (1971) Mental rotation of three-dimensional objects. Science 171: 701–703

Stanovich KE (1999) Who is rational? Studies of individual differences in reasoning. Erlbaum, Mahwah, NJ

Tobin J (2003) To conquer the air: The Wright brothers and the great race for flight. Free Press, New York

Wright O (1988) How we invented the airplane: An illustrated history, (1st ed, 1953). Dover, New York