CHAPTER 6

*Embodied Heuristics**

> Our body is the ultimate instrument of all our external knowledge, whether intellectual or practical.
>
> *Michael Polanyi*[1]

Jean Piaget once said that he could not think without a pen in hand. For him, writing *was* thinking, not simply the translation of thought onto paper.[2] Accordingly, his theory of cognitive development begins with the child's sensory and motor processes, which are eventually transformed into mental life, where they turn into cognitive operations and structures. The general idea that cognition is closely intertwined with action was later called *embodied cognition*. This term has been used for a highly diverse set of ideas, including cognition situated in the environment.[3]

In this chapter, I start with an evolutionary view on intuitive decision-making before introducing the concept of *embodied heuristics*, that is, rules-of-thumb that exploit specific sensory and motor capacities in order to facilitate high-quality decisions in an uncertain world. Models of heuristics take an algorithmic rather than axiomatic approach to represent the process of decision-making. I present a case study of the gaze heuristic that illustrates how an embodied heuristic exploits sensory and motor abilities and how the heuristic has been adapted to the specific abilities of different species. Moreover, the heuristic has also come to solve new tasks created by human culture. I begin with what might have been the first decisions made by living organisms.

The Dawn of Intuitive Decision-Making

The earth is about 4.5 billion years old. Life emerged some 3.8 billion years ago, and animals much later, about 1 billion years ago. It began in

* This chapter is based on Gigerenzer (2021b). [1] Polanyi (1966/2009), p. 20.
[2] Gruber & Vonèche (1977). [3] Wilson (2002).

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the form of single-celled organisms equipped with early versions of sensors and a small repertoire of actions. The best-studied single-celled organism is a bacterium called E. coli (named after its discoverer, the pediatrician Theodor Escherich), which can be found in the lower intestine of humans and other warm-blooded organisms. Its popularity with researchers arises from the observation that it seems not to die, but, instead, splits into two daughter bacteria, which again split, and so on.[4] E. coli can perform two motions, run or tumble, that is, move in a straight line or randomly change its course. It continuously switches between these actions, but when its sensors detect increasing concentrations of food, tumbling is reduced.[5] Here, we see the earliest form of decision-making: bacteria choosing between two actions, run or tumble, guided by chemical cues in their environment. These actions serve adaptive goals, finding food and avoiding toxins. The bacteria rely on decreasing or increasing rates of various chemicals as cues. In decision theory, a cue is a sign, or clue, of something that is not directly accessible, such as food or toxins.

Bacteria are *prokaryotes*, cells without a nucleus. Much later, *eukaryotes* arose from a merger of bacterial cells and eventually formed plants, mushrooms, and animals. Eukaryotes also formed "eyespots," which mark the beginning of vision and allow for further cues to guide action. One of these, light, has a dual function. For some organisms, such as single-celled organisms and plants, light is mainly a source of energy, supplying solar power. Although humans and other animals also sunbathe, for them light is primarily a source of information. Humans *infer* the outside world from patterns of light.

As humans cannot directly see the world, inference is crucial. Our inferences are more elaborate than those of single cells, yet remain intelligent "bets" based on uncertain cues. The great physiologist Hermann von Helmholtz spoke of "unconscious inferences" because even humans are not aware of how they make these inferences, such as reconstructing a three-dimensional world from a two-dimensional retinal image. Unconscious inferences border on magic, given that an infinite number of states of the world are consistent with this retinal image. Through millions of years of learning, sensory and motor abilities have evolved in tandem with heuristics that help to make good inferences in such situations of uncertainty – to find food and mates, to avoid toxins and predators, and to solve the basic goals of organisms.

[4] Khamsi (2005). [5] For a philosopher's account, see Godfrey-Smith (2016).

Along with individual inferences, social behavior evolved. Consider E. coli again. It reacts not only to signs of edible food and dangerous toxins but also to chemicals that signal the presence of other bacteria. This reaction opened the door to the evolution of *coordination* between organisms, that is, social behavior. An example is *quorum sensing* among bacteria living inside of squids. Bacteria produce light through a chemical reaction, but only if enough other bacteria are around to join in. They appear to follow a simple heuristic: The more of the signaling chemical one senses, the more light one produces.[6] The production of light serves its host, the squid, as camouflage. Without this light, predators from below would see the shadow of squids, which are nocturnal animals, as cast by the moonlight. In humans, social coordination takes many forms, including communication, cooperation, and competition, and has led to cultural systems such as churches, political parties, and the market.

Let us now consider a concrete example of how inferences are made based on an embodied heuristic.

Embodied Heuristics: An Illustration

Ants, like humans, make real-estate choices, that is, decisions about where to live, which are essential to their fitness. Consider *Leptothorax albipennis*, a small, approximately 3 mm long ant that lives in colonies with up to 500 workers and a single queen. When their old nest is destroyed, the ant colony sends out scouts to locate a new site with a sufficiently large area to house the entire colony. The ants prefer nest sites that consist of narrow cracks in rocks with flat areas. How can a scout ant estimate the irregular area of a candidate site? A series of ingenious experiments revealed that the scout ants use a smart rule called *Buffon's needle algorithm*, named after the French 18th-century mathematician Buffon, who discovered this millennia after the ants did.[7]

To determine the size of the area, the scout ant first runs for a fixed period (less than 2 minutes) on an irregular path that covers the area fairly evenly. While doing so, it leaves behind a trail of pheromones. After that, the ant exits the area and then returns, where it repeats the procedure of running around in an irregular way. In the second round, the ant counts how often it crosses its own pheromone trail and uses the count to estimate

[6] Ibid., p. 19.
[7] Mallon & Franks (2000). On heuristics shared by humans and other animal species, see Hutchinson & Gigerenzer (2005).

the area of the site: the larger the number of crossings, the smaller the area. This heuristic is amazingly accurate: For a site that is half the size of the area needed, the frequency of crossing is 1.96 times greater.[8]

In Buffon's original problem, the question asked is: What is the probability p that a needle dropped on a floor made of parallel and equally wide strips of wood will end up lying across a line between two strips? For a needle of length l, $p = 2l/\pi t$, where t is the width of the strips. Buffon used the solution to calculate the precise value of number pi. In the ant's heuristic, the lines are the ant's pheromone trail and the needles lying across lines are the ant's crossings of its own trail. The ant is not interested in pi, but in the length t between lines, which indicates the area.

The ant's heuristic involves its body in several ways. First, the ant needs to move about. The heuristic would not work if the ant simply sat still and looked around. Second, the ant's body produces a pheromone trail, which its sensory system has the ability to recognize. These biological functions are necessary for the heuristic to be executed, but it is not sufficient. In addition, the ant needs cognitive abilities such as counting crossings and retaining a memory of the count. Many insects can, in fact, measure and memorize the rate at which they encounter stimuli.[9] All in all, ants have evolved an embodied heuristic to infer the area of potential nest sites.

Unlike the ant's implementation of Buffon's needle algorithm, many models of heuristics do not make reference to specific sensory or motor abilities. An example is the investment heuristic 1/N, which solves the problem of how to invest a sum of money into N assets by allocating it equally. In the uncertain world of stocks, this fast-and-frugal heuristic has been shown to be able to outperform the Noble Prize-winning mean variance portfolio.[10] However, 1/N does not specify or require specific sensorimotor abilities; dividing a sum by the number of assets can also be done by a pocket calculator. Operating a calculator, of course, also requires some motor and cognitive abilities, but these are only needed to operate a machine that does the actual work of finding a solution.

I will reserve the term *embodied heuristic* for rules that require specific sensory and/or motor abilities to be executed. In the section "The Gaze Heuristic," I describe in more detail an embodied heuristic that directs intuition and that humans share with animal species.

8 Mugford et al. (2001). 9 Stephens & Krebs (1986). 10 DeMiguel et al. (2009).

The Gaze Heuristic

When faced with a ball high up in the air, experienced baseball outfielders know where to run in order to catch it. Based on years of experience, most players run guided by intuition, without being able to explain how exactly they intercept the ball. How do they do it? One approach to finding an answer is to treat the question as an optimal control problem and assume close-to-omniscient players who can make complex calculations unconsciously. That is how Richard Dawkins in *The Selfish Gene* thinks a player catches a ball:[11]

> He behaves as if he had solved a set of differential equations in predicting the trajectory of the ball. He may neither know nor care what a differential equation is, but this does not affect his skill with the ball. At some subconscious level, something functionally equivalent to the mathematical calculations is going on.

To determine the trajectory of the ball, consciously or unconsciously, the player has to estimate the parameters in this formula:

$$z(x) = x\left(\tan\alpha_0 + \frac{mg}{\beta v_0 \cos\alpha_0}\right) + \frac{m^2 g}{\beta^2}\ln\left(1 - \frac{\beta}{m}\frac{x}{v_0 \cos\alpha_0}\right) \quad \text{(Equation 6.1)}$$

where $z(x)$ is the height of the ball at flight distance x, measured from the position where the ball was thrown. At $z(x) = 0$, the ball hits the ground. To calculate $z(x)$, the player has to estimate both the initial angle α_0 of the ball's direction relative to the ground and the initial speed v_0 of the ball; know the ball's mass m, the friction β, and that the acceleration of earth g is 9.81 m/s2 (meter/second squared); and be able to calculate the tangent and cosine. Even then, the formula is overly simplified; for instance, it ignores wind and spin. Importantly, the true challenge is not to compute the equation, but to estimate its parameters, such as the initial angle and the initial speed.

Note that Dawkins inserted the term "as if" into his explanation of how players solve the goal. He was well aware that players do not calculate trajectories; they only behave *as if* they did. In his account, what players actually do at the subconscious level remains a mystery. That mystery has been resolved by experimental studies. Experienced players catch a fly ball by using a heuristic that has absolutely nothing to do with calculating a trajectory (see Figure 6.1):

[11] Dawkins (1989), p. 95.

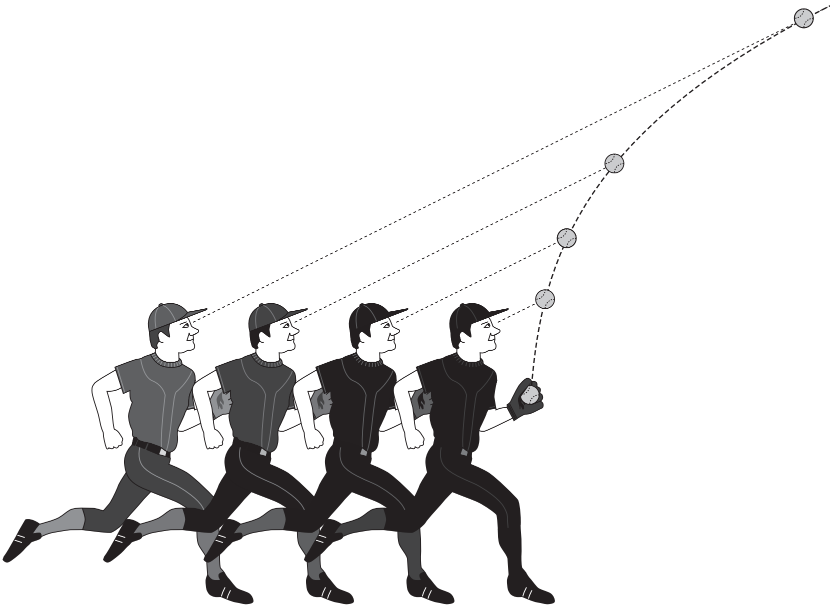

Figure 6.1. Gaze heuristic. The player adjusts the running speed so that the angle of gaze remains constant. The angle of gaze is the angle between the line from eye to ball and the ground.

Gaze heuristic: Fixate your eyes on the ball, run, and adjust your speed so that the angle of gaze remains constant.

The gaze heuristic ignores all the information necessary for computing a trajectory and attends to one variable only, the angle of gaze. In this way, it avoids any measurement errors when estimating the parameters in Equation 6.1. It consists of three "building blocks" – fixating, running, and adjusting – and works in situations where the ball is already high in the air. If that is not the case, the player needs to adapt the third building block:

Fixate your eyes on the ball, run, and adjust your speed so that the image of the ball rises at a constant rate.

One can easily see the logic. If the image of the ball rises at an accelerating rate, the ball will hit the ground behind the player's present position, meaning that the player needs to run backward. If it rises at a decreasing rate, the ball will hit the ground ahead of the player, who then needs to run faster. If the image of the ball rises at a constant rate, the player is running at the correct speed.[12]

The gaze heuristic is an embodied heuristic. It requires the ability to hold one's gaze on an object, to run, and to adjust one's running speed. These abilities are learned early in development. For instance, babies begin to exercise the visual tracking of moving objects at around two months of age, such as tracking the objects in mobiles.[13] These bodily abilities are part of the solution. The gaze heuristic is also an intuitively used rule – as I have mentioned, most players cannot explain the heuristic process they use unconsciously.

Predicting Behavior: As-If Models Versus Embodied Heuristics

Two more general points need to be noted. First, reliance on as-if models rather than process models can mislead researchers regarding the actual goal of an organism. The trajectory calculation model suggests that the player's goal is to determine the point where the ball hits the ground (or is at a height in reach of the player) and then run to this point (see Table 6.1). The gaze heuristic, in contrast, implies that the goal is to

Table 6.1. *The as-if trajectory calculation model and the gaze heuristic compared.*

	Trajectory Calculation	Gaze Heuristic
Player's goal	*Compute landing point*	*Intercept ball*
Prediction 1: Speed	Runs full speed to landing point	The angle of gaze controls running speed and its change. ✔
Prediction 2: Interception	At the landing point, player waits to catch ball.	Intercepts ball while running. ✔
Prediction 3: Course	Runs in a straight line.	Runs in a slight arc. ✔
Prediction 4: Landing point	Knows where the ball is landing.	Does not know landing point. ✔

The as-if trajectory calculation model and the gaze heuristic make different predictions about both behavior and cognitive processes. In addition, they imply different specifications of the player's goal. The checkmarks show the predictions supported by experimental studies.

[12] McBeath et al. (1995); Shaffer & McBeath (2002). [13] Jonsson & von Hofsten (2003).

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intercept the ball. No knowledge about the landing point is necessary; the heuristic leads the player to the ball. A heuristic is not a just an efficient means toward a given end. It can specify what exactly the player wants to achieve. Means can determine ends, not just the other way around.

Now consider the famous argument by economist Milton Friedman that theories should not be concerned with psychological realism, only with good prediction. Friedman illustrated his argument with the story of a billiard player. What the player actually does is of no relevance for Friedman, who just assumed that the player behaves as if they had calculated the ball's trajectory and makes good predictions based on false assumptions. Friedman's as-if philosophy is decidedly antipsychological: Unraveling the process underlying the players' intuition is considered irrelevant. This attitude has been adopted by most economic models, including the as-if utility models in behavioral economics to which free parameters were added.

The gaze heuristic and the study of heuristics in general, however, show a surprising result: Psychological realism can lead to better predictions than as-if models. Let us take a closer look at three predictions about players' behavior.

Consider first the running speed. The trajectory model suggests that players perform better the faster they run to the expected landing point, which provides time for last-second adjustments. In contrast, the gaze heuristic very specifically predicts that players' speed is controlled by the angle of gaze, which determines speed and its change. If players run too fast, they will miss the ball.

Second, consider interception. According to the trajectory model, players should ideally arrive at the landing point before the ball and wait for it. The gaze heuristic, in contrast, implies that players catch the ball while running. The reason is that they adjust their running speed until they catch the ball. In both cases, the predictions following from the gaze heuristic have been supported by experimental studies.[14]

Next, consider the course of running. According to the trajectory model, the player will run straight to the landing point. In contrast, the gaze heuristic can imply, in certain situations, that players run in a slight arc to maintain a constant angle of gaze. These arcs have also been demonstrated in experiments with skilled outfielders.[15]

[14] See, for example, McBeath et al. (1995); Shaffer & McBeath (2002).
[15] Shaffer & McBeath (2002).

Finally, if players consciously or intuitively computed the landing point, as assumed by the trajectory model, they would know where the ball will land. No such knowledge is implied by the gaze heuristic. Studies show that even experienced players have difficulties estimating the trajectory of the ball, its apex, and the landing point, yet are nevertheless able to catch the ball.[16]

The general point is that the as-if trajectory model ignores the heuristic process and, thus, makes incorrect predictions about the resulting behavior. It treats the problem as one of calculating landing points, whereas the heuristic treats it as one of coordination between body and ball. Moreover, the analysis of ball-catching shows that the underlying process is heuristical and embodied.

Coordination Problems

The gaze heuristic and its relatives can resolve various coordination problems. These include interception, such as when athletes catch balls, but also avoidance of collisions, as in sailing and flying. When beginners learn to sail, they are taught a version of the gaze heuristic to infer whether another boat is on a collision course: Fixate your gaze on the other boat; if the angle of gaze remains constant, change your course quickly. When beginners learn to fly a light aircraft, they may be taught a further version of the same rule: If another plane approaches and you fear collision, look at a scratch in your windshield and observe whether the other plane moves relative to that scratch; If it doesn't, dive away immediately – otherwise, that plane might end up colliding with your plane.

The "miracle on the Hudson River" is a famous case where reliance on the gaze heuristic saved lives. On January 15, 2009, US Airways Flight 1549 collided with a flock of Canada geese shortly after takeoff, which shut down both engines. The pilots had to make a life-and-death decision: to try to reach the next airport or attempt a risky landing in the Hudson River. Landing at the next airport would have been the safer option, but only if the plane could actually make it that far. As copilot Jeffrey Skiles explained, to determine whether the sailing plane could safely make it to the airport, they did not try to calculate the trajectory of the plane, but, instead, relied on a version of the gaze heuristic:[17]

[16] Shaffer & McBeath (2005). [17] Rose (2009).

> It's not so much a mathematical calculation as visual, in that when you are flying in an airplane, a point that you can't reach will actually rise in your windshield. A point that you are going to overfly will descend in your windshield.

The point in the windshield rose, which meant the plane would have crashed before reaching the airport. The heuristic helped to make the right decision; all passengers and crew survived the landing on the river.

Note the conscious and unconscious uses of this heuristic, as illustrated by the pilots and the outfielders, respectively. Unlike pilots, most outfielders rely on the gaze heuristic without being able to explain how they catch a ball. Their behavior is intuitive, not based on conscious deliberation.[18] In general, heuristics may be learned consciously, by instruction, or unconsciously, by trial-and-error learning or imitation. The process is the same, a fact overlooked by dual-process theories that align heuristics with unconsciousness and, moreover, assume different processes.[19]

Exaptation

The gaze heuristic was not invented by baseball outfielders. Bats, birds, fish, and other animals rely on it for intercepting prey and mates.[20] The observation that different species rely on the same heuristic invites two possible explanations: *homology* and *analogy*. Homology means that common structures between different species – here, common heuristics – are due to a common evolutionary ancestor. Analogy means that there is a functional similarity based on something else than common ancestors. Whatever the correct explanation is, we can safely assume that the gaze heuristic evolved for predator–prey interaction and not for baseball or cricket.

Cognitive anthropologist Dan Sperber distinguished the proper domain of a cognitive module from its actual domain, that is, the domain for which a module actually evolved from a domain to which it was extended or transferred.[21] Similarly, the term *exaptation* means that a trait or feature acquires a new function beyond its original one derived by evolution. It was introduced as an alternative to the concept of *preadaptation* in order to emphasize that the original function was not connected to the new function.[22] A classic example is the argument that feathers had not evolved for flight with birds, but originally had the function of temperature

[18] Gigerenzer (2007). [19] See Kruglanski & Gigerenzer (2011).
[20] See Collett & Land (1975). [21] Sperber (1994). [22] Gould & Vrba (1982).

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regulation in their ancestors, reptiles. Eventually, feathers became enlisted for a new function, sailing and, eventually, flying. I have not yet seen a discussion of exaptation with respect to heuristics, embodied or not, but the gaze heuristic is a clear case in point. The section "Predator–Prey Coordination" describes its proper domain, or original function.

Predator–Prey Coordination

How does a hawk intercept a duck? Figure 6.2 (a) and (b) shows two strategies for interception. The first is *direct pursuit*, where the hawk flies straight at the duck, that is, takes the shortest path. When the duck changes its position, the hawk changes its direction accordingly, so that the distance between it and the duck is always the shortest possible. The top-left panel shows a case of direct pursuit that ends in a failed interception with a characteristic wavering tail chase.[23] The second strategy is a version of the gaze heuristic, where the hawk does not fly in a straight line toward the duck. Rather, it initially flies toward an expected point X where it would intercept the duck if the latter did not change course (top-right panel). The angle α between the duck, the hawk, and the interception point X defines the angle of gaze. When the duck changes course, the hawk also changes its course so that the angle of gaze remains constant. In geometric terms, the angle of gaze is the base angle of a triangle with equal sides and apex X.

Which of the two heuristics do hawks employ? Studies with headcams mounted on hawks showed that they rely on the gaze heuristic.[24] The comparison between direct pursuit and the gaze heuristic in Figure 6.2 indicates why: Relying on the latter allows for faster interception and avoids the wavering tail chase. Moreover, because the hawk does not fly directly toward the duck, its attack is less obvious. Only when the target is stationary do hawks rely on direct pursuit, that is, fly directly toward the prey.

To be successful in pursuit, an organism needs the ability to adjust speed and direction quickly when the angle changes (due to wind in the case of the fly ball or due to evasive movements in the case of the duck). The number of possible adjustments per second is the *visual cycle rate.* Raptors have a visual cycling rate of about 200 per second, whereas humans have a much lower rate of about 10 per second.[25] The cycling rate corresponds to the length of the path A before it can be adjusted to maintain a constant angle of gaze. The smaller A *is*, the faster is the hawk's

[23] Hamlin (2017). [24] Kane et al. (2015). [25] Hamlin (2017).

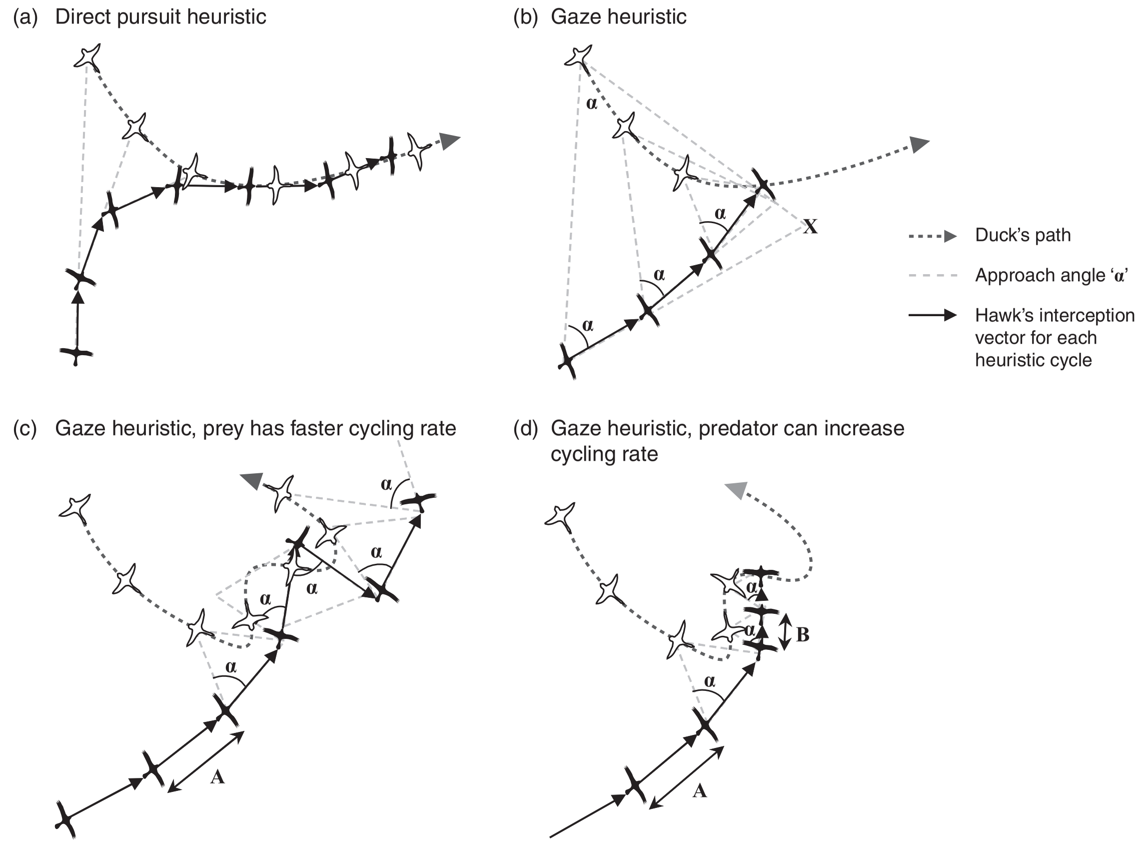

Figure 6.2. Predators (dark hawks) pursuing prey (white ducks). (a) Direct pursuit heuristic: A predator flies in the direction that is the shortest path to the prey and adjusts the direction when the prey changes its course. If predator and prey fly at the same speed, the result is a characteristic wavering pursuit pattern. (b) Gaze heuristic: A predator determines the angle α between the direct line to the prey and the initial estimate X of the intersection point and then adjusts its direction to the subsequent flight path of the duck so that α remains constant. Even when both predator and prey fly at the same speed, the predator can intercept the prey. (c) Gaze heuristic, prey has faster cycling rate: The number of adjustments an animal can make per second is its cycling rate, represented by the length A of its path before it can change its direction. Here, the prey has a faster cycling rate than the predator, which enables it to evade the predator. (d) Gaze heuristic, predator can increase cycling rate: Here, the predator has the ability to increase the cycling rate from A to B, which is higher than that of the prey, resulting in fast interception. Adapted from Hamlin (2017).

cycling rate. Panel (c) in Figure 6.2 shows a prey with a faster cycling rate than the hawk and avoids interception by changing its course before the hawk is able to do so. Thanks to a faster cycling rate, the prey can even get behind the predator. Although the hawk keeps the optical angle constant, it is too slow to adjust. Finally, panel (d) shows a successful predator that increases its cycling rate in the final stage of the pursuit from *A* to *B*.

From Gaze to Echolocation and Whiskers

The gaze heuristic is named after the visual sense, but it has been adapted to other senses, too. Bats rely on the equivalent of the gaze heuristic when hunting moths in darkness, but their interception is based on sound not vision. They use an echolocation system that emits sound as a series of short "clicks" or "calls."[26] When a target is located, the clicks occur more frequently as the bat closes in on a prey. In response to bats, moths have evolved bat-detecting ears capable of hearing the clicks.[27] Outside the bat's detection range, a moth's first reaction is to fly away from the bat. If the frequency of clicks increases, meaning that the bat has detected its prey, this triggers spasms in the moth's wings, resulting in unpredictable flight. Finally, if the clicks peak in a buzz of about 200 clicks a second, the moth's reflex is to instantly freeze to fall out of the bat's path. All this happens within seconds. The bat‘s click rate corresponds to the visual cycle rate of humans and hawks.

The gaze heuristic can also enlist tactile senses. At the final stage of pursuit, mammals such as cats, rats, and seals use their whiskers, an array of long, coarse hairs around the head and mouth that provide information about the prey's position in the final milliseconds before impact.[28] Experiments have shown that rats were less successful in completing an interception of a mouse when their whiskers were removed, and, if they did succeed, the final bite to the neck took longer and was messier.[29]

The Royal Air Force Discovers the Gaze Heuristic

According to a historical analysis, the Royal Air Force (RAF), after some trial and error, was the first to have discovered the gaze heuristic around the beginning of World War II.[30] The problem was that the British controllers who used radar to direct fighters to enemy planes had failed

[26] Denny (2004). [27] Hofstede & Ratcliffe (2016). [28] Grant et al. (2009).
[29] Hamlin (2017). [30] This section is based on Hamlin (2017).

to reach the required 90 percent interception rate. Special calculating devices and increasingly complex mathematics were introduced to crunch the numbers, but to no avail. In this situation, an impatient RAF commander demonstrated that he could meet the 90 percent rate by eye. His system was fleshed out by the Chairman of the Committee for the Scientific Survey of Air Defence (CSSA), Sir Henry Tizard, into a fixed angle approach (the gaze heuristic) and taught to the controllers.

After being trained to use the gaze heuristic, the British controllers no longer sent pilots directly via the shortest distance toward the opponent (the direct pursuit heuristic), but, instead, estimated an intersection point *X*, which determined the constant angle. If the bomber changed course after having recognized the fighter, the fighter was directed to change course too, but keep the angle constant. Shortly before interception, the faster fighter could turn around and meet the bomber frontally, where it was most vulnerable (Figure 6.3). This system became known as the *Tizzy Angle* and was used for the remainder of the war.

According to historical records and training materials, the controllers of the German Luftwaffe relied, instead, on a direct pursuit strategy and appeared to have never discovered the gaze heuristic during the war. In the pursuit control technique, the controller instructs the pilot (who cannot yet see the enemy plane) to fly directly toward the opponent. If the opponent changes course, the pilot is directed to also change course and take the shortest path toward the opponent. The pursuit strategy vectors the fighter behind its opponent, just as the hawk trails behind the duck in Figure 6.2 (panel (a)), and leads to a smaller rate of interception. Although

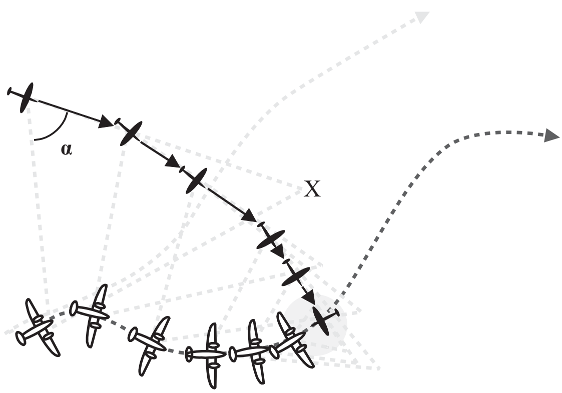

Figure 6.3. British controllers' reliance on the gaze heuristic to direct fighter planes to intercept German bombers. From Hamlin (2017).

the Germans' radar system was superior to that of the RAF in several respects, the British use of the gaze heuristic was devastating to the Luftwaffe and decisive for the Battle of Britain. Robert Hamlin conjectured that the Germans might have won this battle had they linked their high-tech radar system with a gaze-based heuristic control system. In spite of their superior missile technology, including anti-aircraft missiles based on the direct pursuit strategy, the Germans were missing a crucial smart heuristic.

After World War II, the US army combined German missile technology with the British gaze heuristic system into a most successful autonomous guided weapon: the Sidewinder A1M9 short-range air-to-air missile. The missile is a simple, robust interception system whose "gaze" is directed at a point source of heat, which is the target. Once the missile is on its way, it makes continuous inquiries (with a rapid cycle rate) about the changes of the target's position and adjusts its direction so that the angle of "gaze" remains constant. The Sidewinder is still in use in many nations, and new developments appear to be based on the same heuristic of maintaining a constant angle of approach.

Unconscious Intelligence

The gaze heuristic is a particularly interesting example of embodied heuristics. This amazing feat of evolution, a dynamic adaptive heuristic, enables animals and humans to make rapid decisions with the help of a highly automatized system superior to conscious reasoning. I end the chapter with some general insights that this case study provides.

As we have seen, the gaze heuristic is a simple iterative heuristic that adapts to changes in flight path due to wind in the case of a fly ball or due to evasion attempts in the case of prey. It can solve problems in stationary and nonstationary environments and is embodied in the sense that it requires specific sensory and motor capabilities to function efficiently. The astonishing feature of the heuristic is that it has enlisted different sensory capacities in different species, including vision, echolocation, and tactile senses. It also has enlisted various motor abilities. When hawks pursue prey, they implement the gaze heuristic when flying; when dogs catch a Frisbee, they implement the heuristic when running;[31] and when teleost fish pursue prey, they implement the heuristic when swimming. Humans implement the heuristic both in a two-dimensional space, as

[31] Shaffer et al. (2004).

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when trying to avoid a collision with another sailboat, and in a three-dimensional space, as when trying to avoid a collision in the air.

The heuristic has also inspired rethinking financial regulation. Andrew Haldane, the former Bank of England's chief economist, presented his acclaimed Jackson Hole talk entitled "The Dog and the Frisbee" on the gaze heuristic as a model for a safer world of banking. He argued for introducing simple and robust control systems in place of complex regulatory systems, which neither foresaw nor prevented the crisis of 2008.[32] For instance, capital requirements are estimated by calculating the value-at-risk of a bank, which may involve estimating thousands of risk factors and millions of covariation coefficients. The limited success of these estimations recalls the calculations made by the RAF before it discovered the gaze heuristic. The banking system is a fast-changing, nonstationary environment where simple rules can lead to better and more transparent decisions. The standard approach in cognitive science, however, has resembled bank regulation, based on the assumption that more complexity is always better. Journals are filled with highly parameterized models that integrate all possible relevant information, Bayesian or otherwise. Complexity pays for well-defined situations such as games, but leads to overfitting and fragile solutions in ill-defined situations of uncertainty.

Evolution has given us the gaze heuristic, and with it a pointer: To uncover more of the ingenious solutions it has found for a brain the size of two fists, we need a systematic study of embodied heuristics in the real world.

[32] Haldane & Madouros (2012).