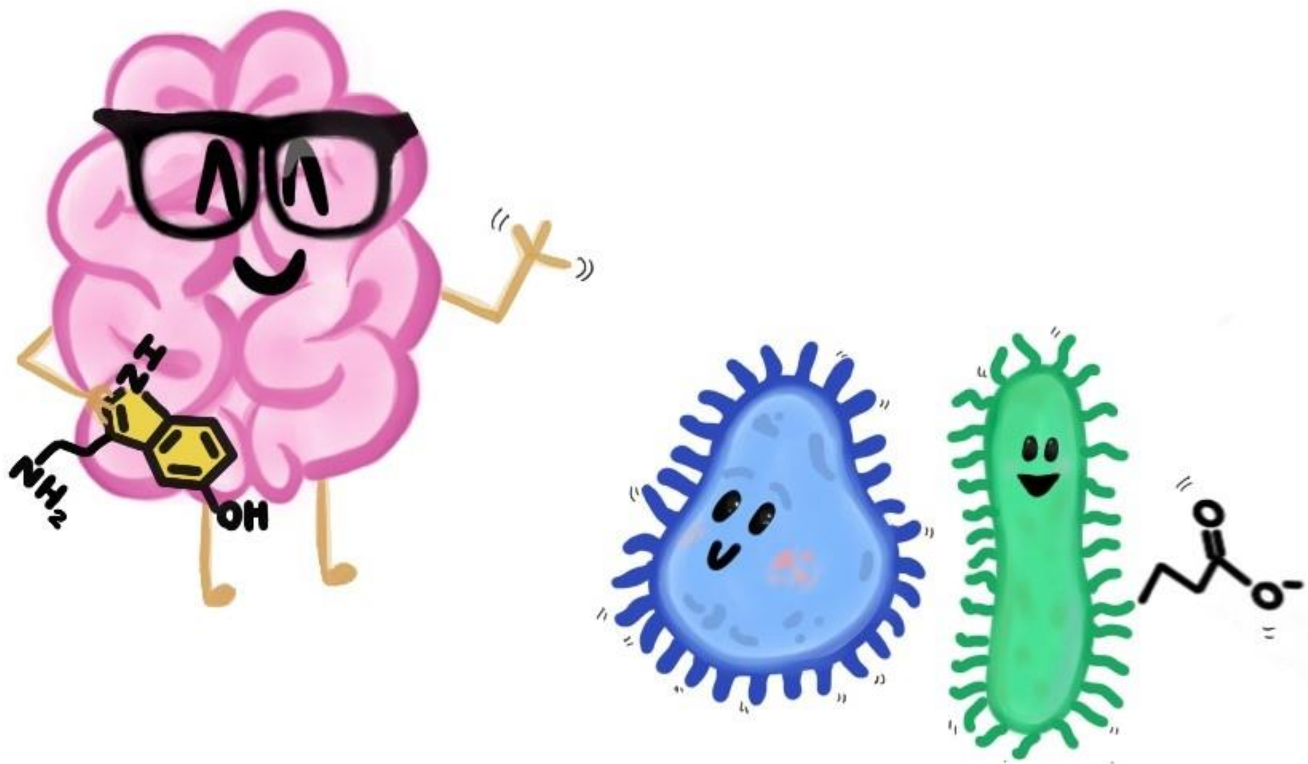
The Gut-Brain Axis

Mommy, what do people mean when they say to follow your gut? Can guts think?



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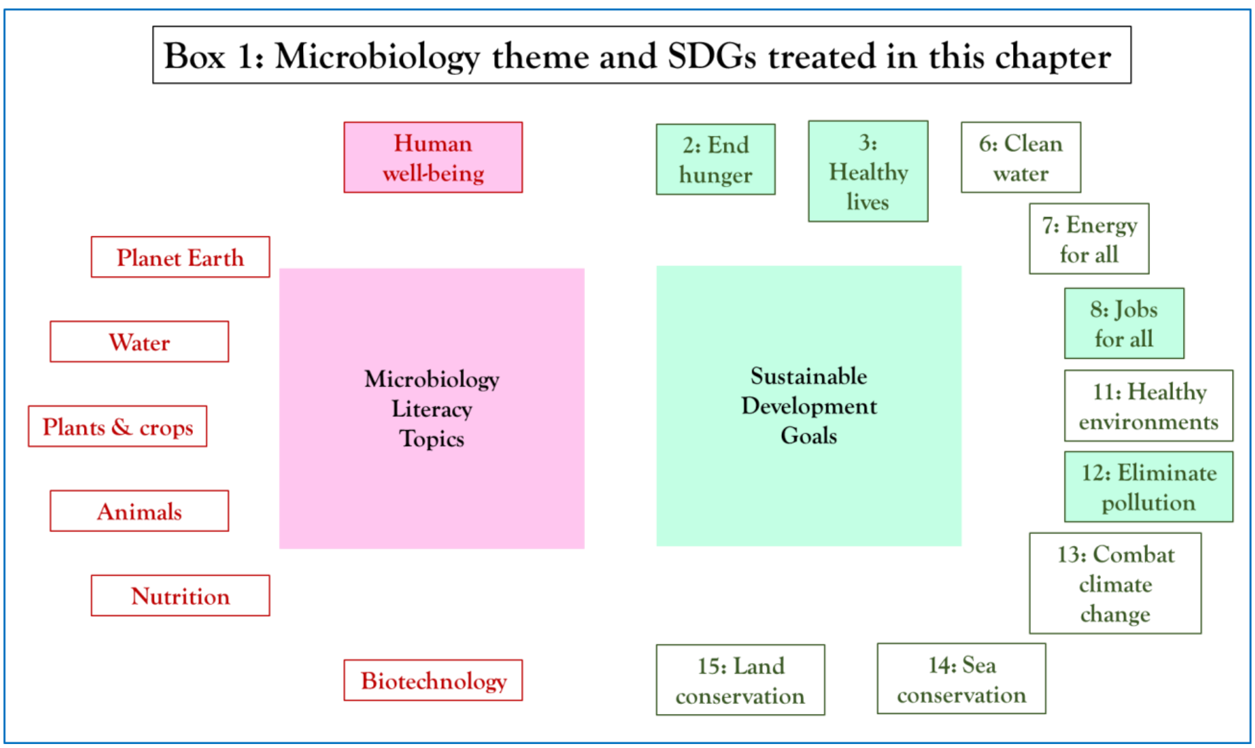
Storyline

Microscopic organisms, or microbes, are greatly misunderstood. Everyone knows that microbes cause infection and disease; it is why we wash our hands after using the toilet and before meals. While certain species of microbes certainly do cause sickness, only about 1400 types of microbes and viruses are pathogenic (harmful) to humans – which is far less than even 1% of all the microbes on the planet! The vast majority of microbes pose no threat to humans; in fact, we rely on the microbes that live inside of our guts to help us regulate a variety of functions such as sleep, muscle control, digestion, and mood. But: unhealthy relationships with our microbes may lead to health problems, such as neurodegenerative disease and addictive behaviour. For this reason, it is very important that we take good care of ourselves by eating healthy foods and exercising, as it helps to support the growth of beneficial microbes. Understanding the role that microbes play in our overall health will help us to design new probiotic therapies that reduce disease and create healthier, happier societies.

The Microbiology and Societal Context

The microbiology: the gut microbiota; gut microbes and brain activities; gut microbes and neurological and neurodegenerative disorders; addiction; food influences gut microbe diversity; antibiotic perturbation of microbiome diversity; antibiotic resistance; exercise and the microbiome; probiotics and prebiotics. *Sustainability issues:* health; food and energy; economy and employment.



The Gut-Brain Axis: The Microbiology

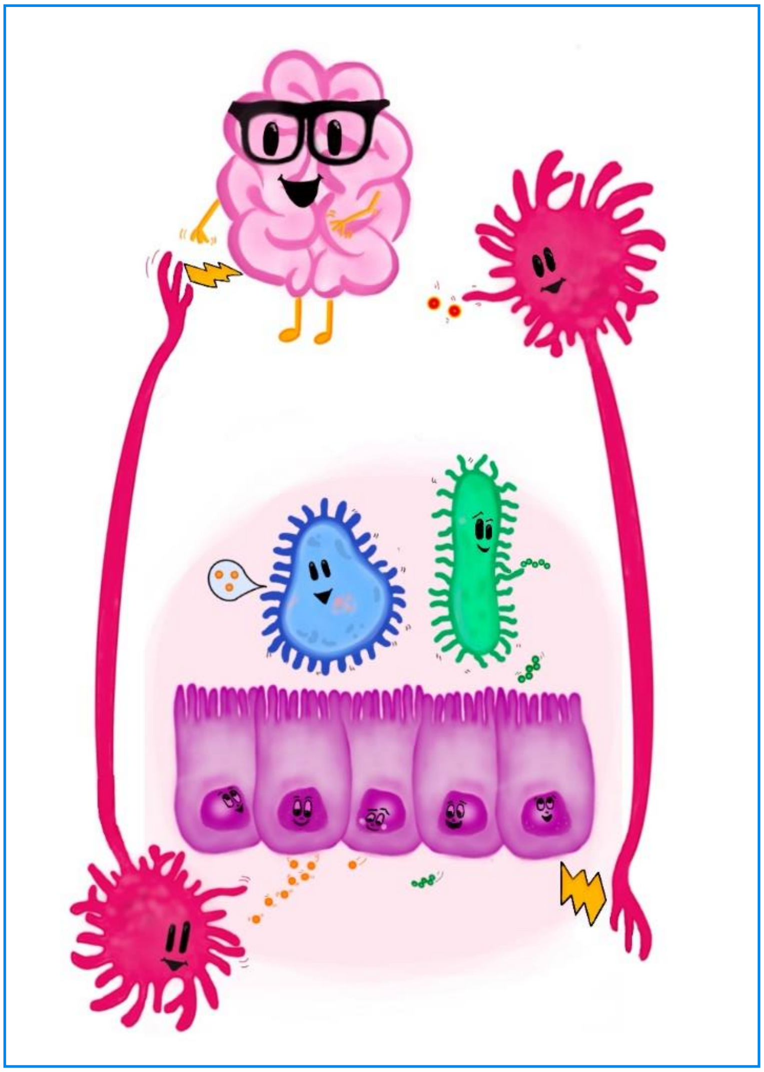
1. ***Your gut is home to trillions of microbes.*** Microbes are everywhere – at the park, in your food, and even in your gut. The vast majority of these microscopic organisms are not harmful to humans, and the ones in your gut are no exception; in fact, in exchange for some of the food we eat and a place to call home, they happily work very hard to produce a variety of important nutrients that we cannot produce by ourselves. This is known as a mutualistic symbiotic relationship, as both we and our microbes benefit from the interaction.

Collectively, these microbes form an ecosystem called the microbiome. Like a rainforest, these microbiomes are at their healthiest when they are full of diverse species. A healthy microbiome has up to a thousand different species of microbes in varying amounts, making each microbiome as unique as a fingerprint! This ensures that no ecological niche is left unfilled. As each microbe consumes and produces a slightly different set of molecules, having a high amount of diversity ensures that your microbiome's 'toolbox' of molecules is also as diverse as possible, ensuring that your body (and your microbiome) is provided with whatever components it needs to thrive. A diverse microbiome is also more easily able to recover after treatments such as antibiotics, and resist against infection, in part as there are no niches available for the pathogenic microbe to occupy and monopolize.

Though the implementation of hygienic practices such as frequent handwashing has dramatically reduced the incidence of many terrible diseases, an unintended consequence of our increasingly sanitary societies has been that our microbiomes are becoming less diverse. Luckily, this can be counteracted by adding microbial diversity in other ways, such as owning a dog (see Pet Dogs by Timmis et al for a more detailed treatment of this subject), eating a wider variety of foods, and playing outside.

2. ***Neurons act as an informational highway between the gut and the brain.*** *Follow your gut, gut-wrenching, a gut feeling*…the English language has several of these gut-centric phrases, and seems to imply that your gut has a brain of its own. While it may not be capable of acing a math quiz, there is a network of brain cells called neurons. Despite being only a fraction of a millimetre wide, these cells can be up to 1 metre long! The 'head' of the cell (called the soma) looks similar to other cells, but has a long, string-like projection that gives the cell its incredible length. Several smaller projections receive signals from the brain, spinal cord, or other neurons; other projections send signals. In this way, the brain can constantly send instructions to most parts of the body and receive information from them about its environment.

There is a certain group of neurons that extends all the way from the brain and wraps intricately around the gastrointestinal tract. These neurons, collectively called the enteric nervous system, are responsible for keeping your gut functioning properly. It is sometimes called the 'second brain', as it can act independently of the brain in your head; however, your brain and your enteric nervous system are constantly sending signals back and forth via the vagus nerve, a string of neuronal cells that acts as an informational highway (Box 2). Some of these signals are food-related, such as telling your brain that you're hungry or full, but more and more evidence is telling us that our guts can influence a wide range of our thoughts and behaviour and can even impact brain health.



Box 2: Gut-brain axis.

Some microbes are capable of making important molecules by themselves, while others tell the intestinal cells to produce certain molecules instead. Some of these molecules may travel to the brain through the bloodstream, impacting a range of neurological functions; others might communicate with the brain by sending electrical signals through nerves.

But where do these signals come from? While some of them are produced by our own cells, there is increasing evidence that many of these signals are products of our microbiome. Understanding how these microbial signals interact with the brain will help us optimize our microbiomes in order to improve our moods, fight addiction, and reduce the rate of neurodegenerative diseases, resulting in happier and healthier societies.

3. The microbes of the intestinal tract are responsible for producing many important molecules, including some that affect mood. Dopamine and serotonin are commonly thought of as 'happy' chemicals, as their release in the brain feels good and improves one's mood. In fact, both molecules play an important role in a wide range of biological functions: for example, dopamine controls muscle function, serotonin helps to digest food, and both molecules help to regulate sleep. These molecules, along with many others, are passed between neurons as a form of communication, and are collectively called *neurotransmitters*. In this way, the brain can receive information about its environment and react to it, often in the form of emotion. Each neurotransmitter has a different role: some like melatonin can make you sleepy, whereas others like adrenaline can give you a burst of energy.

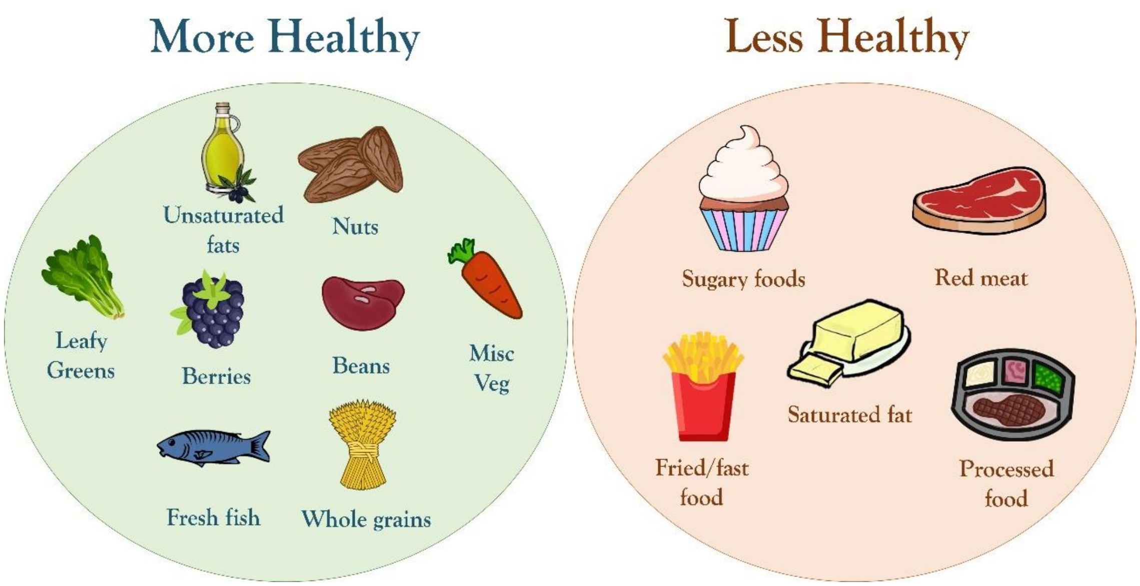
Despite their association with the brain, a wide range of neurotransmitters are produced in the gut (Box 2). Up to 90% of serotonin is made by the cells that line the intestines; incredibly, if there are no gut microbes present (as is the case with germ-free mice, which are meticulously raised in special microbe-free facilities), then these cells produce only about a third of the serotonin that they normally do. Having lower levels of serotonin in the gut can cause depression, anxiety, and even gastrointestinal issues. Other neurotransmitters are produced directly by the gut microbes, such as dopamine. Conversely, some gut microbes can also consume neurotransmitters, reducing the amount available for the brain. Overall, having a microbiome full of beneficial bacteria can help keep neurotransmitters being produced and consumed at a healthy and consistent rate, resulting in better mood regulation and happier people.

4. Changes to the gut microbiome have been associated with a variety of neurodegenerative diseases. Neurons are usually very long-lived cells, and help make up the pathways (called synapses) that the brain uses to make connections and form memories. As we age, neurons and synapses occasionally stop working properly. This leads to things like forgetfulness, which is very commonly experienced later in life: you probably have grandparents who continually misplace their spectacles or keys. However, there are some conditions in which neurons die or become dysfunctional at a rapid rate. Such conditions are classified as neurodegenerative diseases. Each type of neurodegenerative disease has a slightly different target and therefore can have different effects: for example, Alzheimer's disease primarily results in memory loss, whereas Parkinson's disease primarily impacts the person's ability to control their muscles.

Surprisingly, the gut microbiome has become increasingly linked with neurodegenerative diseases over the past decade, where certain types of bacteria are more or less common in people with different diseases. In some diseases like Parkinson's, the patients can start to develop gastrointestinal symptoms such as constipation several decades before their diagnosis! It is not understood whether certain microbes help to cause neurodegenerative diseases or whether the microbiome is simply responding to disease-related changes in its environment, but much work is underway to deduce the answer. People who are diagnosed with a neurodegenerative disease must often stop working and can require costly medical care, involving medication and full-time personal assistance. This can be financially devastating for the individual and their family, and can put a great financial strain upon society as a whole. Neurodegenerative diseases are becoming more and more common as the global population ages, but in the future we may be able to reduce the rates of these diseases by altering the levels of certain microbes in the gut microbiome.

5. Different foods feed different microbes. At any moment, there are billions of microbes living in the human gut, comprising thousands of different species. Each species contributes to the microbiome in a slightly different way and, like humans, often have very different dietary needs. For example, fiber (found in whole grains, fruit, and vegetables) is indigestible by humans but is a prime food source for many gut microbes. These microbes turn fiber into energy, and in turn provide us with molecules known as short chain fatty acids. Like neurotransmitters, these molecules help cells communicate with each other and the brain. For several neurological disorders such as Parkinson's and autism (a developmental disorder that makes social interactions and communication challenging), people with the disorder tend to have different levels of short chain fatty acids than found in neurotypical people, suggesting that these molecules – and by extension, the person's microbiome and diet – may influence the development or progression of the disorder. With rates of neurological diseases and disorders on the rise, preventative measures are desperately needed. The implementation of dietary changes that promote brain health may provide an attractive method of reducing disease burden, as it is widely accessible to the general public and does not require medication (Box 3).

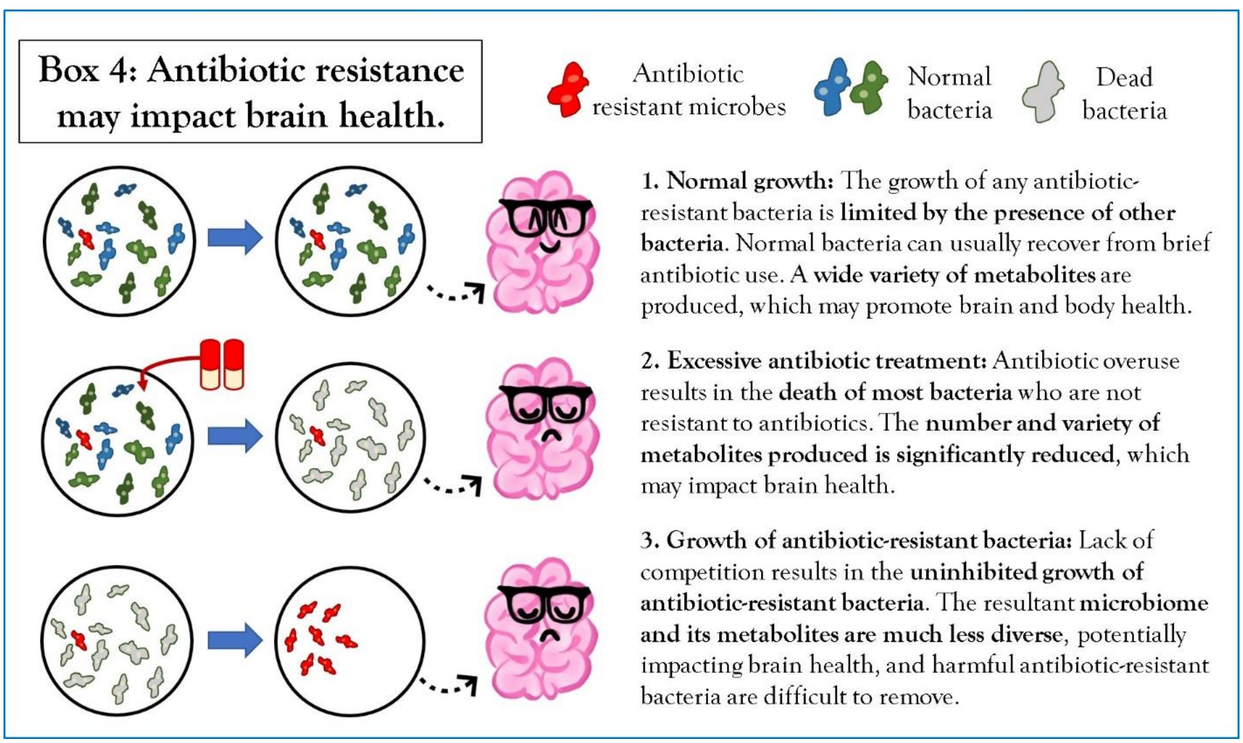
Box 3: Neuroprotective and neurorestorative diets
In general, eating healthy foods helps to promote the growth of beneficial microbes, which in turn provide us with healthy nutrients that promote brain and body health. Several diets have been created that reduce the rate and progression of certain neurodegenerative diseases, and work by increasing the dietary intake of a variety of brain-healthy foods, such as leafy green vegetables, fish, and whole grains, while reducing the amounts of less healthy foods such as fried or sugary foods, hamburgers and other red meats, and processed food such as TV dinners. Part of their success is thought to come from the impact of the diets on the microbiome, though the specifics of this impact are still being investigated. In addition to the neurological benefits, these diets also reduce the rate of other ailments such as heart disease, resulting in an overall healthier population.



6. Changes to the microbiome may influence athletic ability. Professional athletes do their best to optimize their overall health, including eating nutrient-dense meals, maintaining rigorous workout schedules, and minimizing all exposure to other harmful things such as cigarette smoke or excessive alcohol consumption. As a result, athletes have impressively efficient metabolisms and optimized muscle performance. As described in section 5, different foods feed different microbes, all of which provide different amounts and types of energy, vitamins, and nutrients. In addition, some microbes are able to contribute in indirect ways to athletic performance by facilitating faster post-workout recovery times and reducing inflammation. A microbiome that is optimized to provide the maximum amount of resources possible would be of enormous benefit to athletes, as these extra resources may allow them to become more competitive.

There is also increasing evidence that exercise itself can help to promote a healthy and efficient microbiome: multiple studies have found that people who exercise more have higher microbiome diversity and larger proportions of beneficial microbes. Though the causes of these microbial changes are not currently well understood, understanding the impact that the microbiome can have on athletic ability may lead to better, more personalized dietary and exercise regimens. This may help boost professional athletic performance, or may even help improve motor control and stamina of people who are elderly, physically impaired, or who are recovering from injuries.

7. The brain can be impacted by antibiotic use. We provide our gut microbes with energy by eating a wide variety of healthy foods, and in return they provide us with vitamins and other nutrients. But what happens if these microbes are lost? It is common knowledge that the overuse of antibiotics is causing pathogenic microbes to become antibiotic resistant, but another lesser-known side effect of antibiotic use is that beneficial microbes are lost from the microbiome as well. While it is certainly important to use antibiotics in order to prevent or treat bacterial infections that the body cannot beat on its own, their use can have long-term effects on the number and variety of microbes in your gut. This can have a profound impact on their production of nutrients and signalling molecules such as neurotransmitters or short chain fatty acids. Not only can this cause symptoms like constipation or diarrhea, but it can also affect brain behaviour. Mice who were given antibiotics showed impaired memory and signs of depression, suggesting that the gut microbiome is necessary for optimal cognitive health and happiness. By minimizing our antibiotic use, we take an important step toward ensuring that antibiotics remain effective and that our gut microbiome is producing as many beneficial molecules as possible (Box 4).



8. Microbes may play a role in addictive behaviours. We all have free will, but sometimes the urge to do something can be quite strong, regardless of whether or not we *should* do it. Whether it is sugary foods, gaming, etc. (or for adults, perhaps gambling or alcohol), many people struggle with addictions at some point in their lives. One of the most significant risk factors for developing an addiction is stress, where the addictive activity or substance is initially used as a coping mechanism. The effect of stress varies greatly from person to person: the same stressful situation may cause little or no response in some people, whereas others are greatly affected. Interestingly, some of these differences may be due to the microbiota. Mice that were raised without a microbiome had increased levels of stress hormones, indicating that a healthy microbiome might be able to limit the effect of stress on the body and help prevent addictive tendencies from forming.

There is also evidence that modulation of the microbiome may be able to help people recover from addiction. Dopamine is released when a person partakes in their addiction, which is associated with pleasure and helps to lower stress hormones. In addition, several dopamine-related neurological diseases, such as Parkinson's disease and schizophrenia (a neurological condition that causes visual and/or auditory hallucinations), have been previously linked to the microbiome. By understanding the role that the microbiome plays in dopamine regulation, it may be possible to harness the microbiome in order to reduce dependency on any given addiction, leading to more successful recoveries. Overall, addiction is one of the most prevalent mental problems faced today, and understanding the involvement of the microbiome leaves us one step closer to its treatment and prevention.

Relevance for Sustainable Development Goals and Grand Challenges

The gut-brain axis relates to several Sustainable Development Goals, including the following:

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.** Educating the public about brain- and gut-healthy foods will amass large dividends over time, as the general population will be healthier and the rates of many microbially-linked diseases will decrease. Increasing vegetable consumption and decreasing red meat consumption will decrease our global agricultural footprint. Supporting locally grown produce will promote sustainable agriculture and stimulate the local economy.
- **Goal 3. Ensure healthy lives and promote well-being for all at all ages.** By taking care of our gut microbes, we take care of ourselves. It is important to eat healthy foods, take antibiotics only as prescribed by your doctor, and ensure that fast food and sugar remain an occasional treat. These simple yet significant guidelines may not only help to improve your mood and maintain good cognition, but will overall ensure that you harness the full power of your microbiome to maximize your overall health.
- **Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.** The development of a neurodegenerative disease can be devastating for both the individual and their families. The person with the disease often cannot work and may need a full-time carer, which often becomes the job of a family member. As a result, two careers are often impacted by each diagnosis, quite apart from the personal suffering that ensues. Any method of preventing neurodegenerative diseases will allow more people to continue their careers, resulting in higher employment and a stronger, happier society.

- **Goal 12. Ensure sustainable consumption and production patterns.** Reducing our consumption of antibiotics is a critical step for ensuring that our antibiotics remain effective and that our microbial communities remain rich and flourishing.

Potential Implications for Decisions

1. ***Individual***
   a. Limiting antibiotic use (balancing appropriate use with overuse, choosing antibiotic alternatives)
   b. Improving diet (what dietary changes can be made to ensure that the microbiome is well fed?)
   c. Increasing healthy microbial exposure (improving microbiome through pro- and prebiotics)
   d. Non-microbial parameters: overall health benefits of an improved diet, financial cost of high quality diet/supplements, alternative medications/therapies for neurological conditions
2. ***Community policies***
   a. Promotion of locally sourced produce (increased consumption of fruits and vegetables)
   b. Implementation of reasonable hygiene standards (reduction of antibiotic use, exposure to healthy microbes)
   c. *Non-microbial parameters: health costs associated with long-term care facilities (patients with neurodegenerative disorders cannot always be taken care of by relatives), resources available to combat neurological conditions*
3. ***National policies***
   a. Health costs of neurodegenerative diseases, mood disorders, and addiction
   b. National disability programs (careers left due to mental disabilities/afflictions)
   c. Improved health of the overall population
   d. Increased public education on diet and the microbiome and its impact on long-term health
   e. Improved antibiotic usage guidelines and public awareness of their appropriate use
   f. *Non-microbial parameters: Updated national food group guidelines, subsidization of certain food industries*

Pupil Participation

1. *Class discussion on the considerations associated with the gut-brain axis*

2. *Pupil stakeholder awareness*
   a. The existence of the gut-brain axis has an impact on several SDGs. Which of these are most important to you personally/as a class?
   b. What are some steps you can take to reduce your consumption of antibiotics? *(Wash your hands after using the bathroom, don't take antibiotics when sick with a virus, always finish the entire course of antibiotics when prescribed to avoid both a resurgence of the original infection and the need for a second course of therapy/antibiotic, etc.)*

c. What might be done in order to encourage people to eat more microbe-friendly foods? *(Better public education, food programs, subsidizations, etc.)*

3. *Exercises*

a. Some countries and regions have started to implement extra taxes on sugary drinks and sweets in an effort to reduce their consumption. Do you think this is an effective way to promote healthy eating? Why or why not? What other methods might be implemented?

b. Make a list of five common packaged foods that your family eats (granola bars, juice, pasta & pasta sauce, etc). Once you are home, note the amount of sugar present in each food and estimate the number of grams that you would consume in a typical meal containing each item. Which foods contribute the most to your sugar intake?

i. Alternative: try the same exercise with snack foods and saturated fat (chips, fries, cookies, hamburgers, etc.).

ii. For older students: For each food, calculate the percentage of calories (or grams) that come from sugar. Which foods contain the highest ratio of sugar to other ingredients?

c. It can be hard to feel motivated to take care of your microbiome, as it can't be seen directly and the effect on your health is not always immediate. What are some ways in which people can be motivated to develop long-term habits that maximize the health of their microbiome?

d. Many people experience high levels of stress on a regular basis. Aside from taking care of our microbiome, what are some healthy ways in which we can avoid stressful situations or reduce their impact on our wellbeing?

The Evidence Base, Further Reading and Teaching Aids

1. Microbiome: General Knowledge

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2. Neurons: General Knowledge

- https://www.medicalnewstoday.com/articles/320289#synapses
- https://ecampusontario.pressbooks.pub/testbookje/chapter/neurons/
- https://www.verywellmind.com/what-is-a-neuron-2794890

3. Microbes and Mood

- https://www.health.harvard.edu/blog/gut-feelings-how-food-affects-your-mood-2018120715548
- https://atlasbiomed.com/blog/gut-brain-axis-disease-mental-health-influence/
- https://www.bbc.com/future/article/20190218-how-the-bacteria-inside-you-could-affect-your-mental-health

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- Foster, J. A., & Neufeld, K. A. M. (2013). Gut–brain axis: how the microbiome influences anxiety and depression. Trends in neurosciences, 36(5), 305-312. https://doi.org/10.1016/j.tins.2013.01.005

4. Microbes and Neurodegenerative Disease

- https://www.news-medical.net/health/Gut-brain-axis-and-neurodegenerative-disorders.aspx
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5. Microbes and Nutrition

- https://www.medicalnewstoday.com/articles/mediterranean-diet-linked-to-gut-microbiome-improvements
- https://www.mayoclinic.org/healthy-lifestyle/nutrition-and-healthy-eating/in-depth/improve-brain-health-with-the-mind-diet/art-20454746
- https://www.health.harvard.edu/blog/gut-feelings-how-food-affects-your-mood-2018120715548
- https://microbiomepost.com/the-role-of-short-chain-fatty-acids-in-the-gut-brain-axis/
- Mörkl, S., Wagner-Skacel, J., Lahousen, T., Lackner, S., Holasek, S. J., Bengesser, S. A., ... & Reininghaus, E. (2020). The role of nutrition and the gut-brain axis in psychiatry: a review of the literature. Neuropsychobiology, 79(1-2), 80-88. https://doi.org/10.1159/000492834
- Jackson, A., Forsyth, C. B., Voigt, R., Engen, P. A., Ramirez, V., Shaikh, M., & Keshavarzian, A. (2019). Diet in Parkinson's Disease: Critical Role for the Microbiome. Frontiers in neurology, 10, 1245. https://doi.org/10.3389/fneur.2019.01245

6. Microbes and Athleticism

- Mohr, A. E. et. al (2020). The athletic gut microbiota. Journal of the International Society of Sports Nutrition, 17, 24. https://doi.org/10.1186/s12970-020-00353-w
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7. Antibiotics and their Overuse

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- https://www.who.int/news-room/fact-sheets/detail/antibiotic-resistance

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8. Microbes and Addiction

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- Foster, J. A., Rinaman, L., & Cryan, J. F. (2017). Stress & the gut-brain axis: regulation by the microbiome. Neurobiology of stress, 7, 124-136. https://doi.org/10.1016/j.ynstr.2017.03.001
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Glossary

addiction: a habitual, compulsory desire for a substance or activity. Examples include sugar, shopping, and video gaming.

adrenaline: a hormone that increases blood flow and prepares the body for exertion. Produced in high levels in times of stress.

Alzheimer's disease: a neurodegenerative disease characterized primarily by progressive memory loss and impaired cognition.

antibiotics: molecules that cause the death of microbes or inhibit their reproduction. Antibiotics can be broad-spectrum (targeting all microbes) or may target microbes with specific characteristics.

anxiety: a mood disorder characterized by excessive physical and/or emotional stress, including changes in blood pressure and heightened worrying and tension.

autism: a spectrum of neurological disorders that are characterized by difficulties with social interactions, behavioural norms, and verbal/nonverbal communication.

constipation: infrequent and/or difficult bowel movements.

coping mechanism: a strategy adopted to manage stress. Can be healthy (meditation, exercise) or unhealthy (avoidance of the problem, addictive behaviour).

depression: a mood disorder characterized by persistent sadness and disinterest in day-to-day activities.

diarrhea: frequent bowel movements that have high water content.

disease burden: a summary term that describes the total impact of a disease on health, death rates, injuries, and general disability.

dopamine: a neurotransmitter that controls motor function and reinforces behaviours such as consuming sugar or playing video games.

ecological niche: the conditions in which a given species thrives and the role that the species plays in its environment. Includes information on all interactions between the species and other living and nonliving factors in the environment.

enteric nervous system: the complex circuit of neuronal cells that envelop the intestines and regulate their function. Facilitates gut-brain communication.

fiber: indigestible carbohydrates derived from plant tissue. Helps to reduce constipation and supports growth of short chain fatty acid-producing bacteria, which are important microbes for human health.
gastrointestinal tract: all organs that process food and liquids. Includes the mouth, pharynx (throat) esophagus, stomach, small and large intestines, rectum, and anus.
germ-free mice: mice that are raised in a tightly-controlled environment that is completely free of microbes. These mice have no microbiomes.
microbe: microscopic living organisms. Most microbes present in the human gut microbiome are prokaryotes – bacteria and archaea, which consist of a single cell; however, microbes also include protozoa, fungi, algae, amoebae, and slime molds.
melatonin: a hormone that behaves similarly to a neurotransmitter. Produced at nighttime and promotes sleep, thus regulating the sleep-wake cycle.
microbiome: the combination of all microbial organisms present in a given environment. Environments can be inside (ex. mouth, intestines) or outside the body (ex. soil, water).
mutualism: a symbiotic relationship where both organisms benefit from the interaction. An example of mutualism is the pollination of flowers by bees: bees harvest nectar and pollen from flowers. This acts to spread pollen from plant to plant as the bees work, which is necessary for plant reproduction.
neurodegenerative disease: type of disease that results from accelerated death or deterioration of neurons.
neurons: specialized cells that transmit and receive signals. Fundamental cell type of the brain and nervous system.
neurotransmitter: molecules that are used by nerve cells to transmit information.
nutrients: molecules that are essential for life and growth, including vitamins, minerals, and macromolecules (protein, fat, carbohydrates).
parasitism: a symbiotic relationship where one organism benefits from the interaction and one is harmed. Examples of parasites include mosquitoes, viruses, and barnacles.
Parkinson's disease: a neurodegenerative disease characterized primarily by progressive motor function loss.
pathogenic: a descriptive term for microbes and viruses that cause disease.
probiotic: one or more beneficial microbes that are consumed, usually as a dietary supplement, in order to promote the growth of the microbes and improve health. Fermented foods are usually probiotic, such as kefir, yogurt, kimchi, and miso.
schizophrenia: a neurological disorder that is characterized by visual and/or auditory hallucinations. Changes to thought patterns and behaviour often occur, such as increased paranoia and social withdrawal.
serotonin: a neurotransmitter that helps to control mood, sleep, and gastrointestinal function.
short chain fatty acids: derived from indigestible dietary components such as fiber, and produced by certain bacteria. Similar to neurotransmitters, they are important signalling molecules that contribute to gut-brain communication.
soma: the main compartment of a cell, which includes the nucleus and all other organelles. In a neuron, the soma consists of everything except for the many tree branch-like protrusions which are used to quickly send and receive signals between cells.
species: a group of organisms that share common traits and are capable of reproducing. For example, the only currently existing human species is *Homo sapiens*.

stress hormone: hormones, typically cortisol, that are produced in large quantities in times of stress. These hormones cause changes to mood, metabolism, and blood pressure that prepare the body for exertion. Chronic stress often results in high levels of stress hormones, which may cause health problems.
symbiotic relationship: the close association of two living entities. Common examples include humans and their microbiomes (where both benefit – see *mutualism*), and dogs and fleas (where the fleas benefit and the dog is disadvantaged – see *parasitism*).
synapse: the site of interaction between two nerves or a nerve and muscle cell. Signals are transmitted at this site.
vagus nerve: set of two sister nerves that run from the brain to the colon (large intestine) while interacting with the heart and gastrointestinal organs. Receives signals from these organs and transmits them to the brain.
virus: nonliving, submicroscopic entities that are composed primarily of genetic material. Though not all viruses are pathogenic, all viruses must infect living cells in order to grow and/or reproduce.
vitamins: molecules that essential for health and which cannot be produced by the body. Sources of vitamins include diet and microbes.