university of groningen / faculty of science and engineering

EQUIPPING BRAITENBERG VEHICLES WITH LIGHTS AND ITS EFFECT ON THE EVOLUTIONARY PROCESSES OF BRAITENBERG'S EXPERIMENT SIX

Bachelor's Project Thesis

Sanne Berends, s3772950, s.berends.1@student.rug.nl,
Supervisor: Dr H. de Weerd

Abstract: Valentino Braitenberg's experiment six is a thought experiment where a simplified Darwinian evolution is established with a population of simple two-wheeled vehicles that respond to stimuli (light). The evolution is established by placing these so-called Braitenberg Vehicles in an environment with edges, where a vehicle that reaches an edge is replaced by a mutated version of one of the other agents in the environment. Recent research simulated this experiment and observed the evolutionary processes of the population. This study examines the effect of the addition of vehicles equipped with lights on the evolutionary processes. These lights allow the vehicles to be attracted and repelled by each other. This paper sets forth three experiments, each introducing this new type of vehicle to the environment in a different way. The results indicate that the addition of these vehicles results in more varied populations. In addition, behavioral patterns were observed: the emergence of non-moving 'trains' of vehicles, and of static equilibria. These results suggest that the behavior of these new vehicles is less dependent on their environmental set-up than that of regular vehicles.

1 Introduction

In 1986, neuroscientist and cyberneticist Valentino Braitenberg described several thought experiments in his book titled *Vehicles: Experiments in synthetic psychology* [Braitenberg, 1986]. The experiments make use of a collection of simple vehicles; the Braitenberg Vehicles. The behavior of these vehicles depends on their internal structure and the environment they are placed in. In his book, Braitenberg progressively adds features to the vehicles, making their behavior appear more and more complex, and sometimes even human-like. This paper focuses on one of the simplest versions of his vehicles, consisting of only two light sensors, two wheels and two connections from the sensors to the wheels, i.e. the wiring. Adjustable parameters are the sensor strengths, the base rotational speed constants for the wheels, and the connection type. The latter can be either ipsilateral or contralateral, where ipsilateral indicates that the left sensor is connected to the left wheel and vice versa, and controlateral indicates that the connection is crossed, i.e. the left sensor is connected to the right wheel and vice versa. Shaghaghi et al. [2021] implemented a thought experiment by Braitenberg, in which an evolutionary process emerges in a population of these vehicles. This research examines the effect of light-emitting vehicles on the evolutionary processes that they observed.

1.1 Braitenberg Vehicles: Type 2 and 3

In his book, Braitenberg [1986] describes four versions of the vehicle type discussed above, named Aggression, Love, Fear and Exploration. Illustrations of the four vehicles can be found in Figure 1.1. He categorized Aggression and Fear as vehicle type 2, and Love and Exploration as type 3. The names are based on the emotion that seems to cause the behavior of the vehicles. Aggression has a contralateral connection and positive sensor values, which causes the vehicle to turn towards a light source, and drive faster when it gets closer

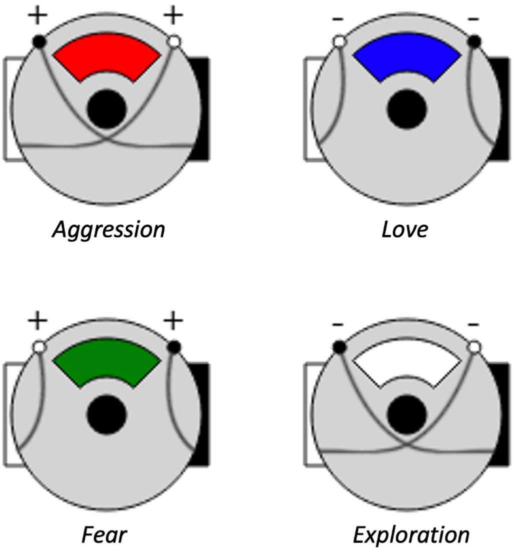


Figure 1.1: Illustrations of the four vehicles of type 2 and 3 as described by Braitenberg: Aggression, Love, Fear and Exploration. The illustrations were taken from de Weerd [2016].

to this stimulus. Love has an ipsilateral connection and negative sensor values, which causes it to turn to the light source but slow down the closer it gets. Fear also has an ipsilateral connection, but positive sensor values. This causes the vehicle to turn away from the light source and drive faster when it is closer to the light source. Finally, Exploration has a contralateral connection and negative sensor values, causing the vehicle to turn away from the light, but drive slower in the presence of the light. In contrast to Fear, it seems to explore the light instead of drive away as fast as possible.

Although the internal structure of the mentioned vehicles is simple, it is not straightforward to guess this structure based on their behavior. The behavior of the vehicles seems to be driven by emotions, even though those are not implemented. Braitenberg discusses this principle in his book. He states that 'downhill innovation' is less difficult than 'uphill analyses'. In other words, inventing simple mechanisms that show complex behavior is easier than determining the internal mechanism based on this complex behavior.

In chapter six, "Selection, the Impersonal Engineering", Braitenberg describes a thought experiment that simulates an evolutionary process. Several vehicles are placed in an environment with edges. When a vehicle reaches one of those edges, it splashes and 'dies'. A splashed vehicle is then replaced by a variation of one of the 'surviving' vehicles. This process contains all main components of an evolutionary process, which are replication, selection and mutation (see Nowak, 2006). When one vehicle splashes, one of the surviving vehicles is *selected* to be *replicated*, then it is altered slightly, which represents the *mutation*. These mutations are explained by Braitenberg as the human error when trying to make an exact copy of another vehicle, and they allow the population of vehicles to evolve over time and get more suited for their environment.

1.2 Darwinian Evolution

The described evolutionary process is a simplified version of Darwinian Evolution. In the nineteenth century, Jean-Baptiste Lamarck was the first person to create a theory of biological evolution, which contrasted with the generally accepted idea at the time, namely that species are static (de Lamarck, 1809, as cited in Nowak, 2006). He believed that species can initiate their own 'improvements', and additionally that their environment forces them to change. With his theory, Lamarck paved the way for Charles Darwin. Darwin proposed that changes in species are unintentional and happen due to chance, a concept which is known as natural selection, as opposed to artificial selection (Darwin, 1859 as cited in Nowak, 2006). Darwin's ideas were inspired by several researchers other than Lamarck, such as Condorcet, Linnæus, E. Darwin, Lyell and Malthus [Avery, 2003].

In 1859, Darwin published a book: *On the Origin of Species* [Darwin, 1859], in which he formulated his beliefs. At the same time, Alfred R. Wallace had also sent him a paper, *On the Tendency of Varieties to Depart Indefinitely from the Original Type*, in which he discussed ideas similar to Darwins beliefs (Wallace, 1858 as cited in Avery, 2003). Together they are seen as the pioneers of the evolution theory as we know it today: the Theory of Evolution by Natural Selection. This theory is sometimes also referred to as Darwinian Evolution.

The key ideas of this evolutionary process, which are also reflected in Braitenberg's experiment six

[Braitenberg, 1986], are that there are populations which can reproduce, all individuals part of a population have descended from the species that existed before them, and genetic diversities in new generations emerge due to mutations. 'Fitter' individuals are the individuals that are more suited for their environment. A population/species with fit individuals therefore has bigger chances of surviving and as a consequence its individuals also have bigger chances of reproducing. Other species may go extinct.

The mathematical biology professor Nowak states that "Wherever information reproduces, there is evolution" [Nowak, 2006]. According to Nowak, all evolutionary processes can be characterized by mathematical formulae to analyse evolutionary dynamics. The key features of evolution, replication, selection and mutation, all have a mathematical nature. This view on evolution allows for a new perspective on Braitenberg's Experiment Six. If evolution is in fact defined entirely by the underlying mathematical formulae, the experiment may offer actual insight in evolutionary processes, instead of functioning as just a thought experiment.

1.3 Realization of Braitenberg's Experiment Six

In 2021, Shaghaghi et al. [2021] realized experiment six as described by Braitenberg [1986]. For the experiment, they used a simulation environment implemented by de Weerd [2016]. This simulation environment allows the user to adjust the number of vehicles in the environment, and the types of vehicles. Furthermore, the number and location of light sources can be altered. Shaghaghi et al. extended this environment so that it contains edges that mark the end of the environment, and when a vehicle reaches this edge, it splashes and is replaced by a mutant variant of one of the remaining vehicles. The mutant is created by multiplying the sensor values by a random factor between 0.9 and 1.1 and it is then placed on a random position in the environment.

The adjusted code was used to observe the evolutionary process of a population of ten vehicles. Four of those were the ones described by Braitenberg, Aggression, Love, Fear and Exploration, and the remaining six vehicles were variations of those. The evolutionary processes were observed in five different scenarios, each of which was used for several trials. Scenario one was an environment with no light sources, scenario two an environment with one light source, scenario three an environment with two light sources, scenario four an environment with three light sources and the final scenario an environment with four light sources. The location of the light source(s) differed per trial.

Shaghaghi et al. found that the evolutionary process often stops due to a dynamic equilibrium being reached. Without this equilibrium, the population would eventually always converge to one type due to drift convergence. The equilibrium starts when no vehicles can reach the edge and thus no new vehicles emerge. This is a result that Braitenberg did not describe. The researchers suggest finding a mechanism that allows the vehicles to overcome this equilibrium. Apart from this, they also found that environmental factors such as the number and location of stimuli, i.e. the light sources, largely impact the evolutionary process. It impacts whether a dynamic equilibrium is reached, or one vehicle type becomes dominant.

The stimuli used by Shaghaghi et al., i.e. the light sources, are static, even though in the real world many stimuli are dynamic. For that reason, this paper examines how dynamic stimuli influence the evolutionary process. To asses this, vehicles are equipped with lights. The vehicles are therefore not only attracted or repelled by the lamps, but also by other vehicles. This could also provide a way of overcoming the dynamic equilibria. Several scenarios will be used to observe the behavior of the vehicles with this new feature. The aim of this study is to find out how, if at all, the evolutionary processes as observed by Shaghaghi et al. [2021] are affected by equipping the vehicles with lights.

2 Methods

For the implementation of the experiment, the simulation environment of Braitenberg vehicles by de Weerd [2016] was used, which is implemented in JavaScript and HTML5. This code was first adjusted to match the workings as described in the study by Shaghaghi et al. [2021]. Most of the design choices and parameters were replicated from their study as much as possible. All parameter values discussed in this section can be found in Table

2.1 Additionally, features were added that allow the vehicles to emit light, either continuously or as a reaction to a certain event in the environment. These features were used to conduct various experiments.

2.1 Environment

Initially, the simulation environment could contain a range of 1-8 vehicles. Each of these vehicles could be adjusted; their type, motor speed and sensors. For the purposes of this study, the number of vehicles was set to 10, and each of the vehicles had a predefined, non-changeable architecture. The number of vehicles and their corresponding architectures were taken from Shaghaghi et al. [2021]. Note that the architectures differ in motor speed constants, sensor strengths and connection type, but that their underlying architecture is the same: they all contain two light sensors, two motors and wheels, and wiring between the sensors and motors that uses a monotonic transfer function. Four of the vehicles described by the architectures correspond to the vehicle types discussed in the Introduction (Section 1): Love, Fear, Aggression and Exploration. The others are variations of those. Since this research used a newer version of the code of the simulation environment, all wheel/motor constants were divided by 5 to imitate the behavior of the vehicles used by Shaghaghi et al. as closely as possible. The architectures can be found in Table 2.2. The vehicles are identified by a unique name and colour. All vehicles were altered to have a radius of 5 pixels.

To allow simulating Braitenberg's Experiment Six [Braitenberg, 1986], the environment needed to have boundaries that mark the edge of the area. The arena of the environment, i.e. the area in which the vehicles move, was resized from 625x400 pixels to 625x500 pixels to match the environment used by Shaghaghi et al.. They experimented with several arena sizes, but this size was used in the majority of their conditions.

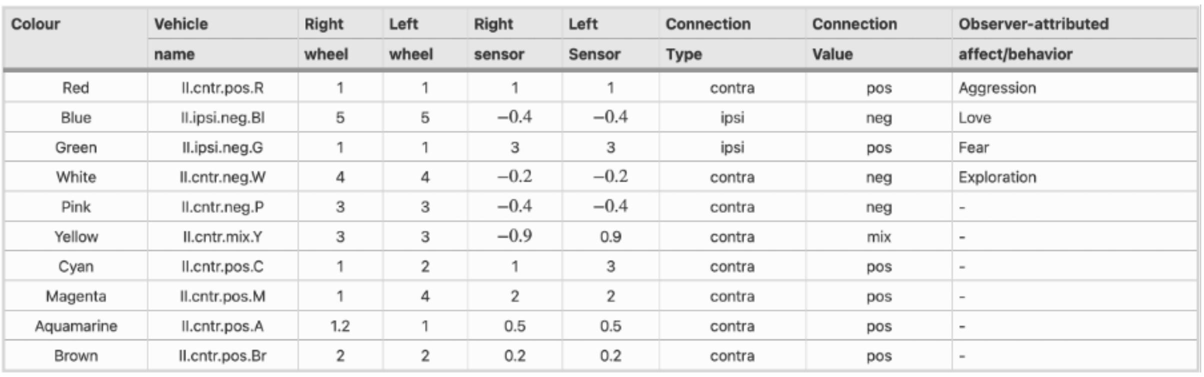
Parameter	Value
n of vehicles	10
Vehicles radius	5 px
Arena width	625 px
Arena height	400 px
Range random multiplication factor	0.9-1.1
Radius light source	2.5 px
Light intensity	5
n of ticks before equilibrium	10,000
n of runs per condition (quantitative)	60

Table 2.1: All parameter settings used in the experiment.

Vehicles that reach the edge of the arena were implemented to be replaced by an alteration of one of the remaining vehicles. Similarly to the study by Shaghaghi et al., it was implemented that the splashed vehicle, i.e. a vehicle that reaches the edge of the arena, is replaced by a new vehicle that 'inherits' all characteristics of its parent vehicle, which was randomly picked from the remaining population. Both its sensor values are multiplied by the same random factor with a value between 0.9 and 1.1. The new vehicle is placed at an arbitrary position in the arena, at least 30 pixels from the edge and not overlapping with any of the other vehicles. The 30 pixels were chosen to give every vehicle an honest shot at surviving, avoiding immediate splashes after a vehicle replacement. In contrast to the study by Shaghaghi et al., where the new vehicle copies its rotational angle from the splashed vehicle, here the new vehicle is initialized positioned in a random angle. This choice was made to make the new vehicle non-dependent on the splashed vehicle. With an eye on the evolutionary process of the experiment, the splashed vehicle is not the 'parent' of the new vehicle. Therefore inheriting a characteristic such as the angle from this splashed vehicle is not realistic.

At the initialization of the environment, Shaghaghi et al. placed the vehicles in a group in the top left area of the arena. To avoid behaviour resulting from this initialization, this research placed the vehicles at random locations in the arena, positioned in a random angle. A constraint is that the vehicles are again at least 30 pixels away from the borders of the environment and do not overlap with other vehicles.

Apart from the vehicles, the initial environment also contained a range of 0-10 light sources, with a light intensity of 5. The size of the lamps was changed from 5 to 2.5 to match the experimental set-up as used by Shaghaghi et al.. The number of light sources, i.e. bulbs, and their corresponding locations were implemented to vary, depending on the phase of the experiment (see Section 2.2). The



Colour	Vehicle name	Right wheel	Left wheel	Right sensor	Left Sensor	Connection Type	Connection Value	Observer-attributed affect/behavior
Red	II.cntr.pos.R	1	1	1	1	contra	pos	Aggression
Blue	II.ipsi.neg.Bl	5	5	−0.4	−0.4	ipsi	neg	Love
Green	II.ipsi.neg.G	1	1	3	3	ipsi	pos	Fear
White	II.cntr.neg.W	4	4	−0.2	−0.2	contra	neg	Exploration
Pink	II.cntr.neg.P	3	3	−0.4	−0.4	contra	neg	-
Yellow	II.cntr.mix.Y	3	3	−0.9	0.9	contra	mix	-
Cyan	II.cntr.pos.C	1	2	1	3	contra	pos	-
Magenta	II.cntr.pos.M	1	4	2	2	contra	pos	-
Aquamarine	II.cntr.pos.A	1.2	1	0.5	0.5	contra	pos	-
Brown	II.cntr.pos.Br	2	2	0.2	0.2	contra	pos	-

Table 2.2: An overview of the ten vehicles used in this experiment. Table taken from Shaghaghi et al. [2021]. In this research the wheel/motor values are divided by 5.

intensity of the bulbs was not altered.

A screenshot of the environment during a run can be found in Figure 2.1. As can be seen in the figure, there is one bulb positioned in the center of the arena. Several vehicles have already splashed, which is the reason some vehicle types appear multiple times. Vehicles are able to move through the bulbs. Therefore, it is possible for vehicles to be gathered at the same position as the bulb. The vehicles then block the light for others.

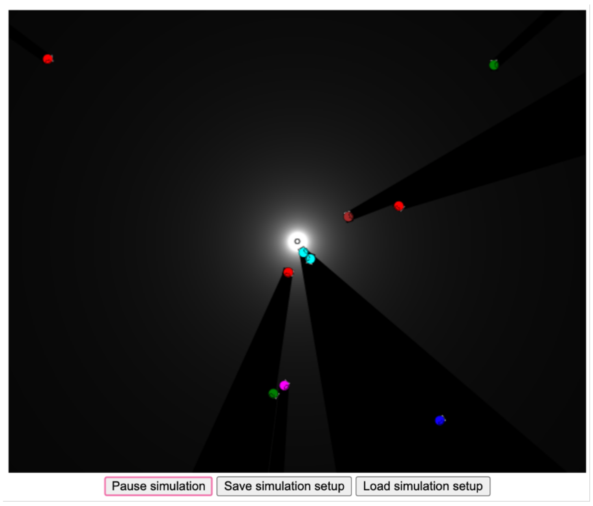


Figure 2.1: Example of the simulation environment during a run, where there are 10 Braitenberg vehicles and a light source in the arena (i.e. the black rectangle). Vehicles of the same color are of the same type and thus share a common ancestor.

2.2 Experimental Set-up

A total of six experiments were conducted. The six experiments were divided into two categories: the quantitative experiments and qualitative experiments. Both categories used the same three experimental set-ups, with the only difference being the number of runs for each condition. Therefore this section details just three distinct experiments. The experimental set-up was inspired by Shaghaghi et al. [2021]. The analyses that were done for the qualitative and quantitative sub-studies were replicated from their research. This enables us to compare the results found in this research with theirs.

One condition is repeated for a fixed number of times, i.e. the runs. Within a run there are several evolutionary iterations (epochs) that correspond to a vehicle splash. A dynamic equilibrium is reached when 10000 ticks, which are simulated clock cycles, have passed without a vehicle splashing. The value was chosen because the qualitative study (see Section 2.3) indicated that within this period of time a dynamic equilibrium had been reached for 47 out of 48 test runs. The exceptional situation where this was not the case is described in the results (see Section 3.1.2). This stop criterion differs from the one used by Shaghaghi et al., who stopped each run after ten minutes. The criterion used in this paper was chosen to avoid continuing runs longer than necessary. The dynamic equilibrium marks the end of a run. An exception is experiment 3, which is explained later in this section.

For each experiment, the same collection of five scenarios were tested. The scenarios mostly correspond to the ones used by Shaghaghi et al. [2021] and each contains a different number of bulbs. These scenarios were in turn divided into various configurations of the bulb(s), i.e. the conditions. Within one condition, the bulb was always placed at exactly the same location, 125 px from the edges (unless specified otherwise). The list below gives an overview of the experiments, where the description of the conditions is omitted for experiment 2 and 3 to avoid repetition:

1. All agents have lights
    a) No bulbs
    b) One bulb
        - Upper left corner.
        - Bottom left corner.
        - Upper right corner.
        - Bottom right corner.
        - Center.
    c) Two bulbs
        - Upper left and bottom left corner.
        - Bottom left and upper right corner.
        - Bottom left and bottom right corner.
    d) Three bulbs
        - Upper left, bottom left and upper right corner.
        - Upper left, upper right and bottom right corner.
        - Bottom left, upper right and bottom right corner.
        - Upper left, bottom left and bottom right corner.
    e) Four bulbs
        - Four corners, 50 px from the edges.
        - Four corners, 100 px from the edges.
        - Four corners, 200 px from the edges.
2. New (evolved) agents have lights
3. All agents get lights at (dynamic) equilibrium

Figure 2.2 provides an illustrative overview of all conditions within one experiment, where the black rectangles represent the arena and the yellow dots represent the bulbs. Experiment 1 is taken as an example. Note that in this paper, a condition is referred to by its number indicating the experiment, then a letter followed by a number indicating the configuration. For example: condition 1c3 refers to experiment 1, the condition with two bulbs, one in the bottom left corner and one in the bottom right corner.

In experiment 1, the vehicles emit light throughout the entire experiment. In experiment 2 only the new vehicles that replace a splashed vehicle emit light, and in experiment 3 all vehicles start emitting light when a dynamic equilibrium has been reached. After the vehicles have been equipped with lights, a run continues until again an equilibrium has been reached.

For this research, vehicles were equipped with bulbs that shine in 360°. The decision to use this type of bulb instead of bulbs that shine angular was based on the fact that the vehicles can now be viewed as a dynamic variation of the bulbs in the environment.

2.3 Analyses

A quantitative as well as a qualitative sub-study were performed. For the quantitative study, several types of data were collected throughout the three experiments. Each condition was repeated for 60 runs to account for variability in runs. For all runs, the composition of the population was recorded at the start of each epoch. This composition refers to an overview of the number of vehicles per vehicle type that the population contains. Apart from this, the number of distinct vehicle types in the population at the end of a run was recorded. Finally, the dominant vehicle type of a run was recorded. A vehicle type is dominant when it has the largest number of members in the population at the end of a run. If there are multiple types with the same, largest number of members, these types are all dominant.

The described data were averaged over the 60 runs of a condition. Due to differences in the number of epochs per run, the number of vehicles per type per epoch were padded. That is, for runs that contained less than 60 epochs, say n, the number of vehicles per type in epoch $m > n$, where $m <= 60$, was taken to be the same as the number of vehicles per type in the equilibrium state (n). The data were then saved to a CSV file, which was used to

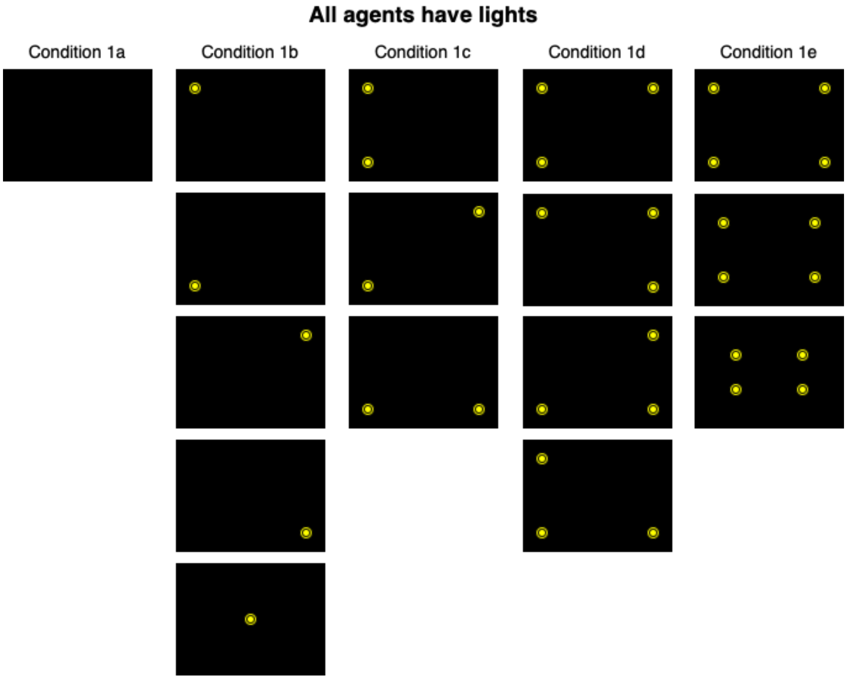


Figure 2.2: Illustrative overview of the conditions of experiment 1, where the black rectangles represent the arena and the yellow dots represent the bulbs.

generate graphs that visualize the data.

For the qualitative study, all conditions of the three experiments were observed for patterns, focusing especially on the behavior of individual vehicles and their behavior as a group, and which vehicle types were represented most in the population (i.e. the dominant species). For each experiment, one representative run was video monitored for illustrative purposes. The recordings can be found on `https://github.com/SanneBerends/BachelorProject`.

3 Results

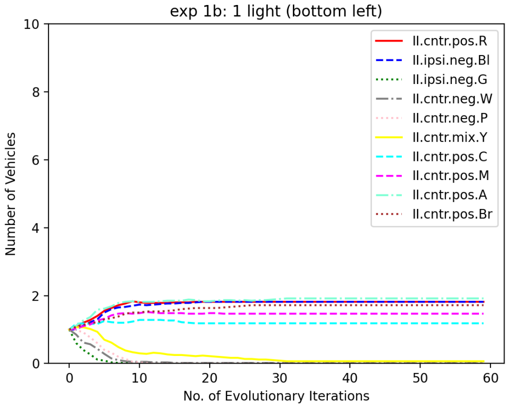
In this section, the results of the qualitative and quantitative sub-studies are discussed per experiment. The quantitative study showed that for the three experiments combined, the mean number of ticks per run was 17,682 (SD = 9,861) and that there was a mean of 11.35 (SD = 8.13) splashes per run.

3.1 Experiment 1: All Agents Have Lights

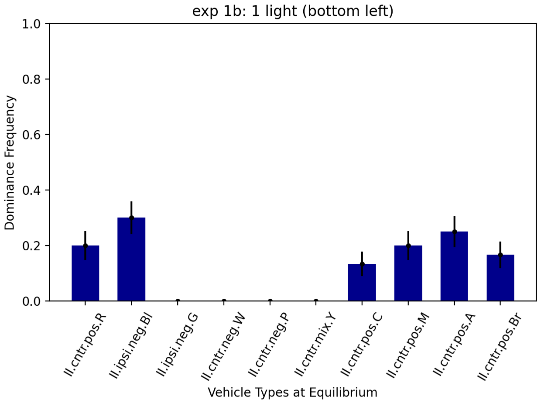
In experiment 1, all vehicles emitted light. First the detailed results are described, followed by some general observations related to the entire experiment. The quantitative results that are described are extracted from the plots that were mentioned in Section 2.3. As an example, the generated graphs of condition 1b2 can be found in Figure 3.1. These results are representative for this experiment. Note that in Figure 3.1b, the frequencies do not necessarily add to 1, due to the possibility of shared dominance. All 144 graphs that belong to this experiment and the other two experiments, can be found on `https://github.com/SanneBerends/BachelorProject/tree/main/Results`.

3.1.1 Granular Results

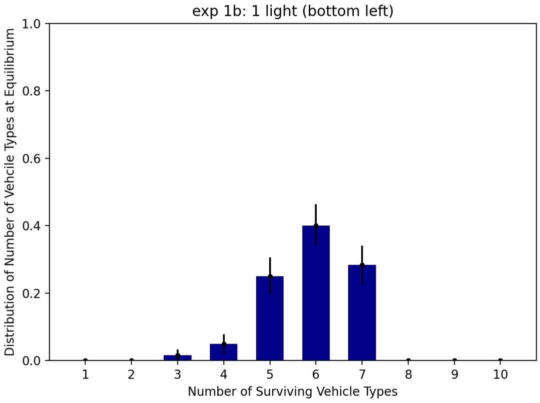
No Bulbs: the majority of the time, the surviving vehicles found each other in the center of the arena. Non-moving ‘trains’ of vehicles emerged and prevented new vehicles from splashing. The trains



(a) The number of vehicles per type per epoch averaged over 60 runs, and their standard deviations.



(b) The dominance frequency per vehicle type in 60 runs, and their standard deviations.



(c) The distribution of the number of vehicle types in the population at equilibrium for 60 runs.

Figure 3.1: Results of experiment 1, condition b2. There was not one vehicle type that stood out for having most members in the population on average (a), nor was there a type that had a significantly higher dominance frequency than other types (b). (c) shows that the number of vehicle types at the equilibrium varied between 3 and 7, with 6 being most frequent.

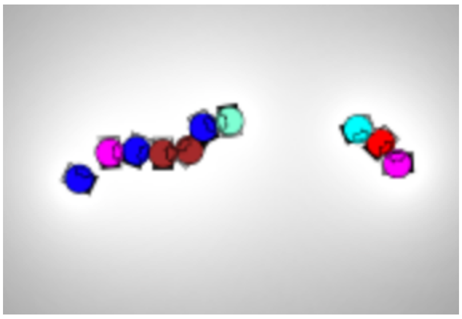


Figure 3.2: Screenshot of a section of the arena where two trains of vehicles emerged.

contained several vehicle types. Figure 3.2 shows an example of two trains that emerged in the arena. Complementing this, the quantitative study indicates that there was not one vehicle type that stood out in terms of its average number of vehicles in the population, nor in its dominance frequency at the equilibrium. Instead, several vehicle types, II.cntr.pos.M, II.cntr.pos.Br, II.ipsi.neg.Bl, II.cntr.pos.R, II.cntr.pos.C and II.cntr.pos.A all performed well, with II.cntr.pos.M having a slightly higher dominance frequency. A visualisation of similar results from another condition can be found in Figure 3.1, where the variation in well-performing vehicles is reflected in 3.1a by the absence of one line positioned higher than the others , and in 3.1b by the number of bars, and the small differences between the heights of the bars.

One Bulb: the addition of one light source to the arena did not seem to have a large impact on the behavior of the vehicles. Again vehicles stuck together and created non-moving trains. The locations of these trains seemed random: sometimes most vehicles went to the light source and a pile-up emerged there, but other times the pile-up emerged somewhere else and attracted other vehicles. There was a variation in dominance of the vehicle types. The same types of vehicles had the highest number of members in the population on average as in the condition with no bulbs, and also the dominance distribution did not differ much (see Figure 3.1a and 3.1b). There were just slight differences between the different configurations, but not enough to conclude that the location of the bulb impacted the evolutionary process. This can be seen in the figures in folders *exp1_b1* - *exp1_b5* on GitHub.

Two Bulbs: the behavior of the vehicles was similar to their behavior when the arena contained one bulb. Again trains emerged, of which the location seemed arbitrary. It was again the same group of vehicle types that tended to be evolutionary successful, especially II.cntr.pos.A, II.cntr.pos.R, II.cntr.pos.M and II.ipsi.neg.Bl, as can be seen in the figures *exp1_c1_graph2*, *exp1_c2_graph2* and *exp1_c3_graph2* on GitHub. These types differed only slightly in dominance frequency within every condition, and therefore there was also not clear difference in results between the different configurations.

Three Bulbs: the behavior of the vehicles in here was slightly different from other conditions. Vehicles now occasionally showed some migrating behavior, where they moved from bulb to bulb until they crashed into another vehicle or a pile-up. The locations of the trains that emerged seemed a little more dependent on the bulb-locations than for the other conditions. The quantitative results are similar to those of the previous conditions: dominance alternated between all the previously mentioned vehicle types.

Four Bulbs: this was the first time that the behavior of the vehicles notably differed per configuration. For condition 1d1, where the bulbs were located 50 px from the edges of the arena, the qualitative study shows that the speed of the vehicles was higher and there appeared to be more splashes than in the other conditions. There was less variety within the population at the equilibrium than for other conditions, as can be seen in graph *exp1_e1_graph3* on GitHub: the number of vehicle types was most frequently 6 and then 5. Condition 1d2, where the bulbs were located 100 px from the edges, showed behavior similar to that observed in earlier conditions. In condition 1d3, there appeared to be less splashes than usual, and more movement in the middle of the arena. For the first time, II.cntr.mix.Y had been dominant, which can be seen in graph *exp1_e3_graph2* on GitHub. Generally, for all three conditions, the same vehicle types as in other conditions were evolutionary successful, especially II.cntr.pos.R, II.cntr.pos.A, II.ipsi.neg.Bl and II.cntr.pos.Br.

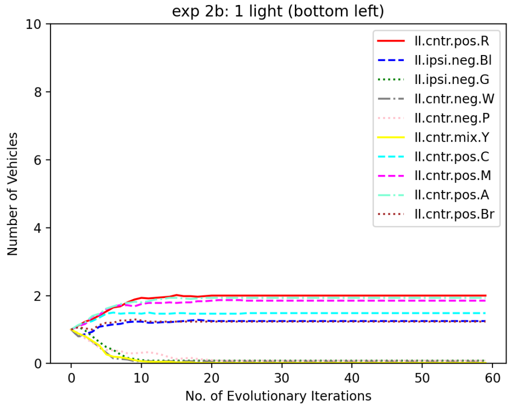
3.1.2 Overall Findings

Some general patterns were observed. In all conditions, trains were formed of vehicles that stuck together. This behavior can be observed in the illustrative video of an example run of experiment 1, where four trains are formed when the equilibrium starts. Since the locations of the trains did not depend on the condition, the overall behavior of the vehicles in this experiment was less dependent on the environment than observed by Shaghaghi et al. [2021]. There was generally also a lot more variety in vehicle types within the population at the dynamic equilibrium then they observed. Furthermore, a general pattern that was observed is that sometimes a vehicle type was dominant for a while due to a favorable initialization position. Also, several vehicles tended to block each other for periods of time, or permanently. This could lead to long periods without splashes, even though no equilibrium had established yet. At the equilibrium, the population usually comprised 6 or 7 vehicle types.

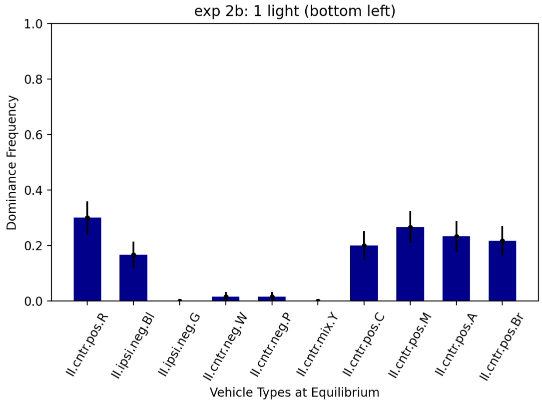
The genetic make-up of the vehicles largely influenced their ability to survive. II.ipsi.neg.G, II.cntr.neg.W, II.cntr.neg.P and II.cntr.mix.Y rarely survived due to their light-avoiding behavior. II.cntr.mix.Y is a special type of vehicle, having one negative and one positive sensor value, causing it to rotate around its axis, whilst slowly moving around. This behavior can be observed in the first seven seconds of the illustrative video of experiment 1. The majority of the time this led to a splash. In an exceptional case, a vehicle of this type took so long to reach the edge that the experiment considered it a dynamic equilibrium, even though there were still chances of it reaching the edge.

3.2 Experiment 2: New (Evolved) Agents Have Lights

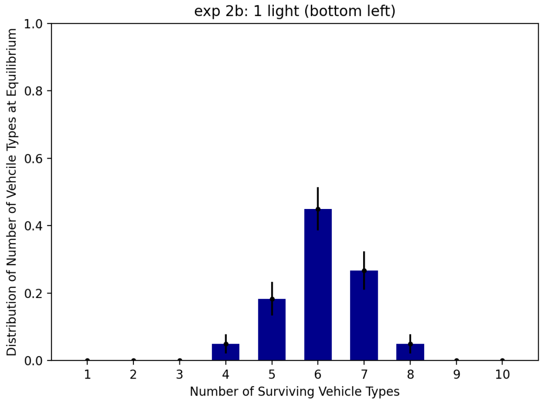
In experiment 2, initially placed vehicles did not have lights, but all splashed vehicles were replaced by a vehicle that emits light. First the detailed results are described and then the overall findings. The quantitative results are, similarly to experiment 1, extracted from the generated plots. Figure 3.3 shows the graphs of a condition that is representative for this experiment (condition 2b2).



(a) The number of vehicles per type per epoch averaged over 60 runs, and their standard deviations.



(b) The dominance frequency per vehicle type in 60 runs, and their standard deviations.



(c) The distribution of the number of vehicle types in the population at equilibrium for 60 runs.

Figure 3.3: Results of experiment 2, condition b2. There was again not one vehicle type that stood out for having most members in the population on average (a), nor a type that had a significantly higher dominance frequency than others (b). (c) shows that the number of vehicle types at the equilibrium varied between 4 and 8, with 6 being most frequent.

3.2.1 Granular Results

No Bulbs: as soon as vehicles splashed, trains started to emerge. Most vehicles gathered around the new vehicles that emit light, and therefore the location of the trains and pile-ups was often close to the initial location of the new vehicles, if those survived. The same vehicle types as in experiment 1 alternated in dominance: II.cntr.pos.R, II.cntr.pos.C, II.cntr.pos.M, II.cntr.pos.A, II.cntr.pos.Br and II.ipsi.neg.Bl (see graph *exp2_a_graph2* on GitHub). In experiment 1, the equilibrium of this condition most frequently contained 6 to 7 vehicle types. Now this was 5 to 6, as can be seen in graph *exp2_a_graph3* on GitHub.

One Bulb: at the start of a run, most of the surviving vehicles were those that gathered around the bulb. There were three main patterns observed: the first is that new vehicles were attracted by the bulb and as a result, there emerged pile-ups there. The second is that the new vehicles were not attracted to the light and splashed. The third is that the new vehicles crashed into another vehicle that was attracted to its light, causing them to create a pile-up of which the location was independent of the bulb. The third situation allowed vehicle types like II.ipsi.neg.G, II.cntr.neg.W and II.cntr.neg.P to survive until the equilibrium and sometimes even become dominant. This is reflected in Figure 3.3b, where there is also a bar for II.cntr.neg.W and II.cntr.neg.P. Compared to experiment 1, II.ipsi.neg.Bl and II.cntr.pos.Br were less evolutionary successful, and II.cntr.pos.C more successful. Apart from that, it were again the same vehicle types that generally performed well. There were only minor variations in results for the five different configurations, as can be concluded by comparing the figures in folders *exp2_b1* - *exp2_b5* on GitHub.

Two Bulbs: again the three patterns occurred that were mentioned above. The same vehicle types as for the other two conditions were evolutionary successful. Notable is that in condition 2c2 II.cntr.pos.Br had a lower dominance frequency than in condition 2c3, as can be seen by comparing graphs *exp2_c2_graph2* and *exp2_c3_graph2* on GitHub.

Three Bulbs: these were the first conditions where there was frequent movement from bulb to bulb, especially by II.cntr.pos.M and II.cntr.pos.C.

This behavior stopped when they crashed into a pile-up. The pile-ups were sometimes located close to a bulb but not always. Several different types became dominant, including II.cntr.mix.Y for the first time in this experiment. This variety in dominance can be observed in the dominance graph of condition 2b2 as well (Figure 3.3b). The same vehicle types as for the other conditions had the highest dominance frequencies and average number of members (see graphs 2 and 3 from folders *exp2_d1* - *exp2_d4* on Github).

Four Bulbs: these conditions were more dynamic. Occasionally, a dynamic equilibrium was observed, as opposed to a static equilibrium where all vehicles are stuck in trains, which was observed for nearly all runs of other conditions. The results are similar to those of this condition of experiment 1: again the three configurations show differences in behavior. Graph 2 from *exp2_e1* and from *exp2_e3* show differences in dominance frequency, and graph 3 from the same to folders indicate that in condition 3e3 there was more variety in the population at the equilibrium than in condition 3e1.

3.2.2 Overall Findings

In all conditions, splashes led to behavior similar to what was observed in experiment 1. Notable is that generally, at the equilibrium the population contained both 'new' vehicles that emitted light, and first generation vehicles. Besides, it was observed that most runs started off relatively slow compared to experiment 1, and as more vehicles splashed, the overall speed increased. Most surviving vehicles gathered around the new vehicles. This can be observed in the video of an example run of experiment 2. The first evolved vehicles are both of type II.ipsi.neg.Bl, and they are initialized in the left half of the arena. Soon, the entire population migrates to the left half.

Most of the behavioral patterns observed in experiment 1 were again present in this study. Again, vehicles could be dominant for a while due to their initial position, but still go extinct afterwards. The genetic make-up impacted the evolutionary process in this experiment. The same vehicle types as in experiment 1 tended to be evolutionary successful. The qualitative experiment showed that compared to experiment 1, the behavior of the vehicles seemed to be influenced more by their environment (i.e. location of the bulbs).

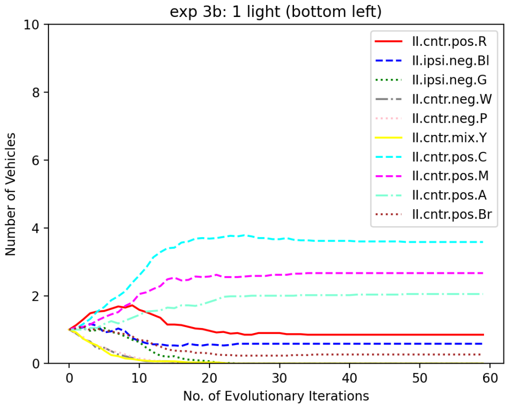
3.3 Experiment 3: All Agents Get Lights at (Dynamic) Equilibrium

In experiment 3, the start of each run was similar to the experiment conducted by Shaghaghi et al.: the vehicles did not emit light. As soon as a (dynamic) equilibrium had been established, all vehicles started emitting light. The detailed results are discussed first, followed by general observations. An example of the results of one condition (condition 3b2) of this experiment can be found in Figure 3.4. Since the results of this experiment varied more per condition than those in experiment 1 and 2, I refer to `https://github.com/SanneBerends/BachelorProject/tree/main/Results/exp3` for the other plots.

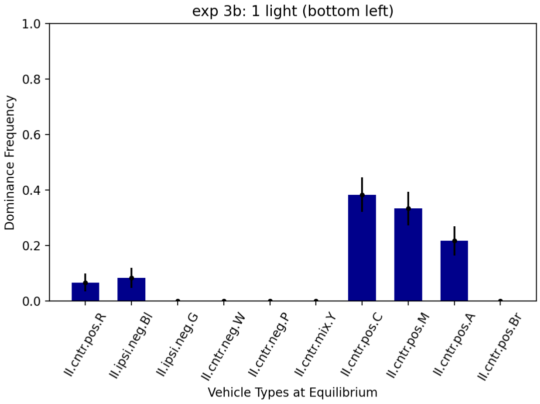
3.3.1 Granular Results

No Bulbs: after a dynamic equilibrium had been formed, the addition of light increased the overall speed, and sometimes led to new splashes. The second equilibrium was then often static. Vehicle types that made circling movements survived more often than other types. This was confirmed by the quantitative study, which shows that these types, II.cntr.pos.C, II.cntr.pos.A and II.cntr.pos.M, had higher dominance frequencies and more members in the population on average. A similar pattern can be seen in Figure 3.4, which also shows in (a) and (b) that II.cntr.pos.C, II.cntr.pos.M and II.cntr.pos.A are most evolutionary successful. These findings are similar to those of Shaghaghi et al.. The population most frequently contained four types at the equilibrium, which is less than in the other experiments. This can be seen in graph *exp3_a_graph3* on GitHub.

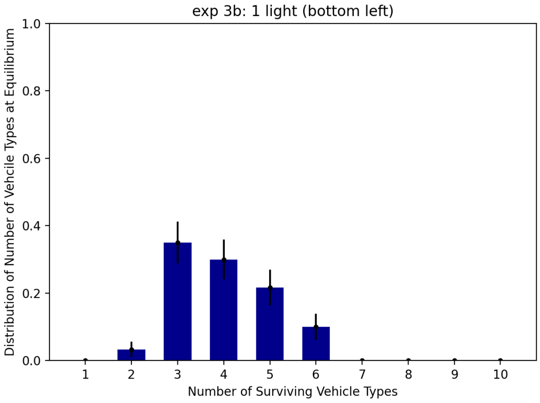
One Bulb: the behavior of the vehicles appeared a lot more bulb-centered than in the other experiments. The addition of light again increased the speed, and always disrupted the formed equilibrium, resulting in new formations: usually non-moving trains. The final locations of these trains seemed random. Again, II.cntr.pos.M, II.cntr.pos.A and II.cntr.pos.C were more evolutionary successful than the other types (see Figure 3.4a and 3.4b). There was less variation within the population than



(a) The number of vehicles per type per epoch averaged over 60 runs, and their standard deviations.



(b) The dominance frequency per vehicle type in 60 runs, and their standard deviations.



(c) The distribution of the number of vehicle types in the population at equilibrium for 60 runs.

Figure 3.4: Results of experiment 3, condition b2. On average, the population contained most vehicles of type II.cntr.pos.C for most epochs (a). This type did not have a significantly higher dominance frequency than other types (b). (c) shows that the number of vehicle types at the equilibrium varied between 2 and 6, with 3 being most frequent.

in experiment 1 and 2. As can be concluded from Figure 3.4c, the population at the equilibrium most frequently contained 3 vehicle types.

Two Bulbs: the qualitative study shows occasional movement from bulb to bulb of vehicles before and during the dynamic equilibrium. Afterwards trains were formed again. The same types were evolutionary successful as in the previous condition (see Figure 3.4a and 3.4b for similar results). Notable is that the differences in results between the three configurations are larger than in experiment 1 and 2. For example, II.cntr.pos.M has a higher dominance frequency in condition 3c3 than in 3c1 and 3c2. This can be seen by comparing graphs *exp3_c1_graph2*, *exp3_c2_graph2* and *exp3_c3_graph2* on GitHub.

Three Bulbs: in these conditions, the vehicles showed more migrating behavior from bulb to bulb, creating new movement in already established pile-ups. Most vehicles were located close to a bulb at the (dynamic) equilibrium. The addition of lights again caused vehicles to form trains. The same types as in the other conditions were evolutionary successful: II.cntr.pos.M, II.cntr.pos.C and II.cntr.pos.A best, but also II.cntr.pos.R, II.cntr.pos.Br and II.ipsi.neg.Bl, as can be seen in graphs 1 and 2 from folders *exp3_d1* - *exp3_d4* on GitHub.

Four Bulbs: the results of the three configurations with four bulbs again differed from each other. Bulbs located closer to the edge caused more splashes. II.cntr.pos.R and II.cntr.pos.M had the highest dominance frequency (see *exp3_e1_graph2* on GitHub). There was little variation within the population at the second equilibrium: graph *exp3_e1_graph3* shows that the population most frequently contained 3 types at the equilibrium. Bulbs located further from the edge caused more movement in the center of the arena. Even after the equilibrium, when the vehicles emitted light, there was still movement around the initial bulbs. II.cntr.pos.M, II.cntr.pos.A and II.cntr.pos.C performed best, as can be seen in graph *exp3_e3_graph1* and *exp3_e3_graph2* on GitHub. There was more variation within the population at the final equilibrium than when the lights were located closer to the edges (see *exp3_e3_graph3* on GitHub).

3.3.2 Overall Findings

This experiment showed more variation between conditions than the previous two experiments. The environment had a larger impact on the evolutionary process. This, combined with the genetic makeup of the vehicles, determined which vehicles survived until the end. The qualitative study shows that even though the first, usually dynamic, equilibrium was always disrupted by the addition of lights, this rarely changed which vehicle type was dominant. Often, there were some new splashes as a result of the addition of lights, but those splashes usually only led to a change in the number of vehicle types at the final equilibrium. Generally, the population contained less vehicle types at the equilibrium than in the other experiments. However, there were more types than observed by Shaghaghi et al..

Some general patterns were observed during this experiment. The addition of lights at the equilibrium increased the overall speed of the vehicles. However, the vehicles often quickly reached a second equilibrium, usually static, due to pile-ups. The location of those pile-ups seemed random. The video of an example run of experiment 3 shows this behavior: first a dynamic equilibrium is reached. The addition of lights causes no new splashes, and finally 4 static trains are formed, marking the beginning of a (static) equilibrium. Dominance between runs varied due to the random starting position of the vehicles, but generally, vehicle types that rotate around their axis and that are attracted to light, survived. More specifically, the vehicle types with unequal motor values were most successful.

4 Discussion

This research experimented with the effect of equipping Braitenberg Vehicles [Braitenberg, 1986] with lights on the evolutionary processes in a simulation of Braitenberg's Experiment Six. Three experiments were conducted. Each of them introduced these light-emitting variations of the vehicles to the population in a different way.

The results suggest that the addition of vehicles that emit light impacts the behavior of the group of vehicles, as well as the evolutionary process. The individuals in a population with light-emitting vehicles formed trains. Since the vehicles in these trains were generally not able to move away, the participating vehicle types survived. As a result, the population contained more variation at the end of a run than observed by Shaghaghi et al. [2021].

The location of the trains was arbitrary most of the time, suggesting that the behavior of vehicles equipped with lights is less dependent on their environmental set-up, i.e. the number and location of bulbs, than regular vehicles. Instead, the behavior of the vehicles was more dependent on the other vehicles, and also on their genetic make-up. Vehicles that are attracted to light and have unequal motor values tend to survive in all conditions.

Furthermore, similarly to Shaghaghi et al., the population rarely converged to one dominant type. Instead, an equilibrium was reached in most conditions, where no vehicles reached the edge of the arena and thus the evolutionary process stopped. However, where the equilibria observed by Shaghaghi et al. were usually dynamic, the ones observed in experiment 1 and 2 and the second equilibrium of experiment 3 were static the majority of the time. This again seemed to be caused by the formation of trains.

Although these results appear to be caused by the addition of lights to the vehicles of Braitenberg's Experiment Six, it cannot be ruled out that other factors play a role. A limitation of this research is that the population that was used was not an exact copy from Shaghaghi et al.. Due to the use of a new version of the simulation environment, the behavior of the vehicles was imitated as closely as possible, though not the exact same. We cannot say for sure if this caused deviations in the observed evolutionary processes. Besides, some of the design choices were different than those of Shaghaghi et al.. An example is the initial position of the vehicles. Deviations in these choices may also have influenced the evolutionary processes.

However, this research does contain an experiment that consists of both a phase with 'regular' vehicles only, as well as a phase with light-emitting vehicles only: experiment 3. This sub-experiment therefore starts as an regular implementation of Braitenberg's Experiment Six, similar to that used by Shaghaghi et al., but then with our population and design choices. The runs showed that in the first phase, the behavior of the vehicles was more dependent on the condition and thus the environmental set-up than in the second phase. The first phase usually ended in a dynamic equilibrium and the second in a static equilibrium. Therefore, we can draw similar conclusions from the observations of this experiment as from comparing the results of experiment 1 and 2 with the results of Shaghaghi et al..

The characteristic that makes the Braitenberg Vehicles interesting is their simple structure in combination with their seemingly complex behavior. This is the reason Braitenberg named them after emotions. In a way, the addition of a light source to the vehicles has simplified their behavior as a group: the surviving vehicles form trains in the arena. There was less bulb-to-bulb behavior observed, and equilibria were often reached quite quickly. However it is interesting to look at these results with a little bit of imagination, since this is what Braitenberg himself did when designing the thought experiment. The population containing light-emitting vehicles forms groups (i.e. trains) that find each other and stay together even though some of the participating vehicle types might not survive as an individual: you could see this as friendships. Some groups collapse when a new vehicle joins: you could see this as fights. Finally, some vehicles chase after another vehicle for the entire run, until either of them splashes: you could see this as a one-sided friendship or love. So although the observed behavior may not have seemed as complex as in a population of regular vehicles, the resulting group dynamics did appear complex, and with a little imagination even human-like, although this was not implemented.

This study leaves enough room for further research. A possible extension is to investigate the effect of angled lamps on the evolutionary processes, as opposed to the 360 degrees bulbs that were used in this research. The use of angled lamps allows for a simulation with vehicles more like real-life vehicles, which have angled lamps at the front and the back.

Another suggestion for future research is to adjust the light intensities, so that the static light sources are brighter than the light that is emitted by the vehicles. This way, the environmental set-up might have a larger influence on the evolutionary process, even though vehicles can still attract and repel each other.

Finally, another suggestion is to examine the effect of dynamic light sources in the environment. These can be either combined with the regular vehicles, or with the light-emitting vehicles. This may provide a way of overcoming the dynamic equilibria as observed by Shaghaghi et al., or the static equilibria as observed in this study.

To conclude: this study describes some interesting behavioral patterns of a population of evolving vehicles, some or all of them emitting light. Three different experiments were conducted. These experiments could provide a foundation for other experiments that investigate the effect of dynamic light sources on the evolutionary process in Braitenberg's Experiment Six.

References

J. S. Avery. *Information Theory and Evolution.* River Edge, N.J.: World Scientific, 2003.

V. Braitenberg. *Vehicles: Experiments in Synthetic Psychology.* Cambridge: MIT Press, 1986.

C. Darwin. *On the Origin of Species by Means of Natural Selection or the Preservation of Favoured Races in the Struggle for Life.* London: J. Murray, 1859.

J. B. D. M. de Lamarck. *Philosophie Zoologique: Ou Exposition des Considérations Relatives à l'Histoire Naturelle des Animaux*, volume 1. Paris: Dentu, 1809.

H. de Weerd. Braitenberg Vehicles. `http://www.harmendeweerd.nl/braitenberg-vehicles/`, 2016. Accessed: 28 Feb 2022.

M. A. Nowak. *Evolutionary Dynamics: Exploring the Equations of Life.* Cambridge, MA: Harvard University Press, 2006.

S. Shaghaghi, O. Hamid, and C. L. Nehaniv. Valentino Braitenberg's table: Downhill innovation of vehicles via Darwinian evolution. In K. Wojtkiewicz, J. Treur, E. Pimenidis, and M. Maleszka, editors, *Advances in Computational Collective Intelligence*, pages 57–72. Cham: Springer International Publishing, 2021.

A. R. Wallace. On the tendency of varieties to depart indefinitely from the original type. In *Journal of the Proceedings of the Linnean Society*, volume 3, pages 53–62. London: Longman, Brown, Green, Longmans and Roberts and Williams and Norgate, 1858.