A Review Article On The Intuitive Visualization Of The Perceivable Effects of Special Relativity

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ABSTRACT

When people hear 'Theory of Relativity' they consider it to be a complex and abstract field of physics. This is partially because no prominent effects of the theory are visible in our day-to-day life, which is majorly governed by Newtonian Physics which is a simplification of Relativistic Physics at the slow velocities found on Earth. This issue is overcome by numerous attempts at the visualisation of the Theory of Relativity to make learning the theory more intuitive. This review article specifically attempts to create a comprehensive review of milestones in visualising Special Relativity with a focus on the perceivable effects rather than measurable ones. Detailed explanation of the different measurable and perceivable effects followed by looking at 5 milestone attempts at visualisation from 1945 to the present day looking at their progress in both accuracy and intuitiveness. This article aims to serve as a starting point for readers in understanding the perceivable effects of Special Relativity as well as a guide to look into different visualisations to aid in their learning.

KEYWORDS

Special Relativity, Perceivable Effects, Intuitive, Visualization, Light Runtime Effect, Doppler Shift, and Relativistic Aberration of Light

INTRODUCTION

The theory of Relativity consists of two interrelated theories, Special Relativity & General Relativity, proposed in 1905 and 1915 respectively. Both of them were theorised and published by Albert Einstein. Special Relativity theorises the 4-dimensional spacetime and the interconnection between space and time from different reference frames. Special Relativity is so named because it looked at a specific scenario, inertial (non-accelerating) reference frames in flat spacetime with no quantum and gravitational effects. General Relativity generalises this theory to include reference frames in warped spacetime and refines Newton's Law of Gravitation by defining gravity as a geometric warp in spacetime due to the presence of mass [1].

Before Einstein came up with special relativity there was a huge contradiction between two major theories of physics, Newton's Laws of Motion and Maxwell's Equations for Electromagnetic Fields. Maxwell theorised that light moves at a fixed speed ***c****(299792458 m/s or* 3×10^{8} *m/s)* for any inertial reference frame. Now let's consider body **A** and body **B** that is moving at a relative speed of 0.5***c*** away from **A**; **B** also has a light emitter that emits light in the direction of motion. As per Newton's Laws of Motion, body **B** observes the light to travel at velocity ***c*** but body **A** observes the light traveling at 1.5(0.5+1)***c***. This contradicts Maxwell's equations and Special Relativity is the leading theory that solves this contradiction. Special Relativity has two postulates (assumptions accepted to be true to form the theory):-

- **The Principle of Relativity**, which states that the laws of physics are the same for any inertial reference frame. This principle relies on the fact that there is no possible way to find the absolute velocity of an object as it will be different relative to different reference frames.
- **The speed of light in a vacuum is constant**, at the speed of ***c***, for all reference frames regardless of the motion of the reference frame or the light source.

With these Einstein theorised, with the help of a thought experiment, that for the speed of light to remain constant the other variables in the relation of speed (speed=distance/time), distance and time, need to change. This leads to Time Dilation, an observer will see a moving clock tick slower compared to a clock at rest relative to them and Length Contraction, an observer will notice a moving object look 'squished' in the axis of movement compared to the same object at rest. These changes happen according to the Lorentz Transformations, a set of spacetime coordinate transformations that occur in such a way that the speed of light remains constant for all inertial reference frames. The effects of special relativity and these transformations though are only seen at very high velocities, a significant fraction of ***c***. At speeds close to what we usually experience in our daily lives the equations of special relativity can be approximated to form Newton's Laws of Motion. This is why Newton's Laws of Motion had so much supporting evidence and are still used for calculating the motion of objects. [2]

- **Perceived Effects of Special Relativity**

The Lorentz Transformations are noticed if the time or distance are measured changes, but our perception-defined as how we will sense our surroundings (specifically seeing in this case)- of objects and space around us while travelling at the near light speeds at which relativistic effects are noticeable will be different from the measured Lorentz transformations; space will seem to warp and even colours and brightness of the surroundings will change. The following are perceived changes that an observer travelling at near-light speed will notice compared to an observer travelling at much slower speeds (at the order of magnitude that we experience motion in our daily lives):-

1. **Light Runtime Effect:** Length Contraction suggests that an observer moving at near-light speeds will notice their surroundings to get all 'squished' together (from the reference frame of the observer they are at rest while their surroundings move past them). This thought process is flawed because it assumes that light will instantly reach the observer, while in reality, light takes a finite amount of time to reach the observer; an observer always sees an object's past. As an observer approaches an object head-on at near-light speeds light from the closer end of the object reaches the observer significantly faster than the further end, just like with galaxies far away. The observer sees the far end from further back in time compared to the closer end, they see the past of the object. This causes the observer to receive light (hence information) about the object from different points in time. Since the object is moving relative to the observer it seems to stretch laterally.
   The previous scenario was for an object approached head-on by an observer. Still, when the object has a relative motion that is not head-on - either cause it is to the left or right of the observer or because it is moving at an angle from the observer - it gets more complicated as Terrell Rotations are noticed where the faces of an object facing away from the observer become visible. This happens because, at these relativistic speeds, the

object moves away before it can obstruct the light emitted/reflected by the faces pointing away. In fact, spheres remain spherical in perception but the texture on the sphere shifts as the previously non-visible sides become visible.
This is an observable example of how relativity breaks simultaneity, two simultaneous events for one observer might happen at different times for another observer moving at relativistic speeds relative to the first observer.

2. **Length Contraction:** While Length Contractions might not affect our perception in the way we expect them to but an inertial moving observer **A** at near-light speeds will notice that the time taken to travel from one point in space to another (in a straight line) will be less than predicted by Newtonian Physics and this difference in time taken will increase along with the speed at which the observer travels. From the observer's reference frame, everything around them is moving and according to Length Contraction, the measured distance between the two points will decrease and hence the observer will take less time than a now contracted spacetime.

$$l' = l\sqrt{(1 - c^2/v^2)}$$

l' = length measured by an observer outside the frame of reference

l = length measured by an observer inside the frame of reference

v = speed of the object

c = speed of light

3. **Doppler Shift:** The frequency of any wave emitted from a moving body increases in the direction of motion and decreases in the opposite direction. As light is a wave this is true for light sources too. A scenario with an inertially moving observer and a stationary light source/reflector, if considered from the reference frame of the observer, seems like the observer is at rest while the light source/reflector is moving. Thus the observer will notice a Doppler shift. With light, this effect is only noticeable at near-light speeds.

$$f' = f(c + v_o)/(c - v_s)$$

f' = observed frequency

f = actual frequency

c = velocity of light

v_o = velocity of the observer towards source

v_s = velocity of the source towards the observer

4. **Relativistic Aberration of Light:** An inertial observer at near-light speeds will have more photons hitting it in the direction of motion and fewer in the opposite direction. This makes the objects in the direction of motion brighter and those opposite the direction of motion darker. This effect is commonly known as the 'Headlight Effect'

5. **Time Dilation:** Time dilation is not perceivable until the observations include two stationary clocks that initially started at the same time, and at the moment of observation one clock is moving at near light speeds relative to the other and the observer. The observer will see that the clock in motion ticks slower than the stationary clock.

$$\Delta t' = \Delta t / \sqrt{(1 - c^2 / v^2)}$$

Δt' = time observed by an observer outside the frame of reference

Δt = time observed by an observer inside the frame of reference

v = speed of the object

c = speed of light

It is important to remember that special relativity is for a special scenario that is inertial motion. If we consider two people, one who stays on Earth and another who heads for an intergalactic mission to Andromeda and then comes back at near light speeds then the observed effect will be different. This is because the travelling person changes direction and hence becomes a body with two separate legs of travel with inertial motion. This situation is famously known as the twin's paradox in which the person on Earth ages quicker and is hence older than the travelling person.
[3]

- **Visualisation of Special Relativity**

Special relativity is one of the pillars of modern physics, but because of the extreme (near-light speed) conditions needed to observe its effects, it appears complex and is difficult to comprehend and perceive. A lot of attempts have been made to visualise special relativity intuitively. These attempts have changed from simple thought experiments to illustrations, then simulations, and in the present there even exist educational games that use special relativistic physics models to make their environment and teach the diverse effects of special relativity. There are still several limitations to even the most recent attempts at a complete visualisation.

DISCUSSION

Mr. Tompkins in Wonderland

George Gamow wrote short stories in the form of Mr. C.G.H Tompkins' adventures in a universe where the limit of the speed of light is much lesser than that of our universe and what he saw. The stories used illustrations and logic to describe and depict length contractions as well as time dilation in this imaginary world. The simplicity of these thought experiments and illustrations helps make the concepts easy to understand and comprehend fully. Gamow also incorporates simple mathematics to add depth to the concepts he explains. These short stories cover the basic concepts of special relativity well. Where they lack though is that they do not paint a complete picture. The stories ignore the presence of simultaneity which would cause the Light Runtime Effect, Doppler Shift, and the Headlight Effect to be missing from consideration in the stories. Due to this, the illustrations end up forming a misleading image, where it seems that the measurable effects are also the perceived effects of special relativity [4].

This set of short stories though still deserves a lot of credit since it is the first attempt to visualise special relativity and make it intuitive and easier to understand for the general public.

Sights That Einstein Could Not Yet See

U. Kraus, H. Ruder, D. Weiskopf, and C. Zahn worked on a series of computer-generated simulations in the form of short sub-60 sec films to have 'the main visual effects of special relativity explained in a simple and intuitive way'. The paper was inspired by Mr. Tompkins and its attempt to visualise and hence explain a concept not usually encountered in our daily Newtonian physics-led life. They also fixed the errors in George Gamow's short stories and their lack of the light runtime effect in the visualisations. The set of short films in this paper includes the first popular visualisation of the Terrell rotation and the Light runtime effect. The paper does touch on relativistic aberration and the Doppler shift but the simulations are lacking in comparison to the others in terms of realism, and intuitiveness. Another limitation of the simulations is that they are non-interactive and relatively short, only displaying a short duration of repeated motion. Each simulation also focuses on only one specific scenario rather than multiple at the same time, all of them ignoring chromatic aberration and Doppler shift except for one simulation. Being non-interactive lowers their intuitiveness [5].
These films were some of the first to use computer-generated simulations to create a visualisation of special relativity and provided a milestone for future attempts at visualisation.

Real-Time Relativity

Real-Time Relativity is a computer software developed by C. M. Savage, A. Searle, and L. McCalman. It plays like a game in a relativistic world with several objects of varied shapes that the user can navigate through at near-light speeds. It was developed for use in education so that students can have a better understanding of special relativity, something usually considered to be an 'abstract' topic. This is the first interactive simulation of a relativistic world, which allows users to be in control, take their time with the software, and properly experience a relativistic world. The variety of objects present allows users to see all kinds of visual effects like Terrell rotations and spheres remaining spherical. It also has a few clocks that allow users to see time dilation and its effects. What this software does notdisplay though is the Doppler shift and relativistic aberration of light. It also uses mainly abstract objects and planets to display the effects, while this is more accurate since it displays a non-warped section of space-time free from general relativity-defined effects, this decreases intuitiveness since the user moves around in an environment more abstract and separate from reality. Another limitation of this software is that all objects are stationary besides the observer, this limits the software to non-dynamic systems. The user does move and 'accelerates' by increasing its speed per second rather than a continuous gradual increase. This gives the effect of acceleration but the calculations can be made using that of an inertial body with different velocities at different times[6].

Being the first interactive software though it explored a method of increasing intuitiveness not explored before, gamification. Gamification has several advantages, the main one being that most people have played some form of game so when handed simple navigation controls it is easy for people to jump in and explore the software. The idea of gamification is what makes the next two attempts at visualisation very intuitive.

Open Relativity And A Slower Speed of Light

Open Relativity is a game-making toolkit that runs on Unity, a popular game engine. It was developed by Zachary W. Sherin, Ryan Cheu, Philip Tan, and Gerd Kortemeyer at MIT Game Lab. The toolkit allows users to apply relativistic physics in Unity and simulates the visual and measured effects of special relativity. They also developed a game using the toolkit called ‘A Slower Speed of Light’ where the players collect tokens in an open world and as they collect these tokens the speed of light decreases making relativistic effects more apparent. Both the game and the toolkit were developed to aid in education, to make learning special relativity more intuitive and fun, and for research, making simulation-based research in special relativity easier and more approachable. Open Relativity can simulate all of the effects mentioned in the Introduction and all of them simultaneously. A slower speed of light does a great job at displaying Doppler shift and relativistic aberration of light, along with the other effects. Like real-time relativity, the toolkit allows interactive real-time simulations, but Open Relativity also allows moving objects beside the viewer, though they do still have to be inertial. This is because Open Relativity, like Real-Time Relativity, does not calculate for gravitational effects, the toolkit does not have gravity or acceleration. The user does ‘accelerate’ but this is achieved similarly to Real-Time Relativity[7].

Open Relativity and A Slower Speed of Light brought a change to the field of visualizing relativity. It turned it into something more accessible while not lacking in accuracy. It also used the concept of gamification to make the simulation very intuitive.

Velocity Raptor

The last attempt at visualisation is very interesting in the fact that it is a flash game, called Velocity Raptor, developed by an individual who goes by the name Andy. The visualisation does not have complex 3d environments that require high computational capabilities, nor does it need to be downloaded- running online. It is developed for a site called TestTubeGames that aims to make interactive and educational science projects. In the game, the player plays a velociraptor that solves 2d puzzles in a world with a slowed-down speed of light as he runs around the puzzle room. The game uses a narrative to explain the basics of measured and perceived special relativity and is a more complete game experience than A Slower Speed of Light. The game involves accurate warping of the room to match the Light runtime effect and includes length contraction, time dilation, and Doppler shift. The game does not calculate relativistic aberration and being a 2d game does not display Terrell Rotation. Being 2d also means that the game is not accurate to real life but makes up for that in the form of a game that is very intuitive, explains concepts and effects observed, and is fun to play and challenging too[8].

Velocity Raptor is not as ambitious as the other attempts but is focused on making something that makes learning special relativity fun and still has mathematically accurate calculations. It is very intuitive and being available online it is very accessible.

CONCLUSION

Attempts discussed in this paper show the progress over time in visualising the perceivable effects of special relativity, especially in an intuitive manner. All these attempts are milestones for this task. The general limitation for all of them was the computational power at the time of their making, something that still stands true. Special relativity is a complex theory with several complex equations behind it and properly turning this into a simulation is not easy. Incorporating General relativity is an even tougher task that requires even more computational power which is why all of these attempts ignore accelerating bodies. The progress made over time though is still remarkable and the issue of computational power will only decrease over time. Making a subject like physics, which seems abstract to many, intuitive is an important step to spread its awareness. The theory of relativity is always thought of as a complex and abstract theory beyond what humans could possibly experience but these attempts at intuitive visualisation combat that narrative, making teaching and understanding special relativity easier and even fun.

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