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Regular Article

Genetic analysis on color concept construction process: Looking for operational invariants

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ABSTRACT

This paper presents the findings of an ongoing longitudinal research study. The study involved 63 children, aged 8 to 10, who were students in a public school in Brazil. The objective of this research was to identify the operational invariants used by children when constructing color concepts in situations using a projector. We analyzed the solutions proposed by the children and their own draws, employing Bardin's Content Analysis as our methodological approach. By applying the Theory of Conceptual Fields, we identified their operational invariants. The results indicate that children's understanding of colors stems from their ability to differentiate between different levels of brightness and darkness. Our original contribution lies in the use of Conceptual Fields Theory's analytical framework to evaluate the conceptualization process of colors in a broader context.

1. Introduction

This work is part of a broader project which aims to describe and categorize the operational invariants (Vergnaud et al., 2009) used in situations involving the concept of color, from children in early childhood education to adults. Our research project aims to understand the temporal evolution of concepts related to color formation across various phases of human development, operating under the hypothesis that, at different stages of development, the levels of comprehension and task resolution will vary. Consequently, we plan investigations that employ identical task types, enabling us to assess how diverse research subjects apply their knowledge in action. This approach allows us to attempt to construct potential routes of conceptualization over time.

In a first approach, we carried out the research in children aged 5–6 years (Carvalho & Souza, 2017) in Brazil. We then investigated children aged 8–9 in Portugal (Zacarias et al., 2020).

In this work, we present results of a research conducted with 63 children between 8 and 10 years-old from a public school in a small city in Brazil over 180 min of intervention. Our main research problem was formulated as follows: which are the operational invariants (Vergnaud et al., 2009) used by children to resolve situations involving the formation of colors?

Drawing upon the Theory of Conceptual Fields proposed by Vergnaud (Vergnaud, 1990), we developed a set of practical activities to evaluate the solutions they presented to various problems encountered during the interaction. Specifically, our attention was focused on interpreting the nature of the children's verbal and written responses, as well as their drawings during the process of problem resolution. This approach enabled us to gain a more nuanced understanding of the conceptual frameworks and mental models employed by children as they engage in problem-solving activities.

The significance of this study is multifaceted. First and foremost, it holds intrinsic importance within the realm of optics education. The exploration of the temporal evolution of color conceptualization contributes significantly to a profound comprehension of fundamental concepts related to light and image formation. These concepts are extensively covered in early science education, laying the foundation for university-level studies. The comprehensive understanding of how the concept of color forms and evolves over time not only enhances our insights into optics but also provides valuable input for the development of effective teaching programs and educational materials.

On a secondary level, the application of quantitative research methods and the utilization of a theoretical framework rooted in cognitive psychology place this research within the broader landscape of investigations into the conceptualization process. The longitudinal nature of this study is instrumental in identifying invariant factors in the

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construction of scientific concepts, transcending specific research themes. Consequently, a notable contribution of this research project lies in advancing our general understanding of potential socio-cognitive trajectories in the conceptualization process.

The investigation of children's conceptualizations of colors is situated within a larger context of research on physical knowledge. Specifically, the work conducted at the Geneva Center for Genetic Epistemology by Piaget (Piaget, 1927, 1967) serves as a foundational reference for understanding the construction of notions related to physical causality and the nature of reality. This type of knowledge is deeply rooted in everyday experiences and intuition (Viennot, 2002).

Research focused specifically on the formation of colors, such as that conducted by Guesne (Guesne et al., 1985), has suggested that children think color as an intrinsic characteristic of the observed object. This conclusion is consistent with the study conducted by Feher and Rice (Feher & Rice, 1987).

Feher and Meyer (Feher & Meyer, 1992) employed a differentiated methodology that utilized colored lights for the visualization of objects in a non-school space. The study involved children between the ages of 8 and 13 who visited a science museum, where experiments were conducted in closed rooms illuminated with primary colors (red, green, and blue). The most significant conclusion of this study was that most of the children interviewed considered color to be a degree of darkness.

In the order hand, Gonçalves and Carvalho (Gonçalves & Carvalho, 1995) focused specifically on the strategies employed by children between 8 and 11 years old to solve problems related to the formation of shadows. Drawing on Piagetian research, the authors identified several stages in the development of this notion. Initially, children view shadows as a substance, before moving on to seeing them as a reflection of the object. Finally, they acquire an understanding that shadows are created by the absence of light. The methodology employed in this research reflects the authors' interest in investigating the construction of causal relationships when performing shadow projection tasks.

Castro and Rodriguez (Castro & Rodriguez, 2014) developed a new approach to teaching color addition to students, using a model they developed called the ATC (Addition Table of Colors). Applying the Conceptual Change Model, the authors developed a didactic sequence and tested it with 250 students, comparing it to traditional teaching with another 204 students. They found that the ATC model was more effective in promoting a critical understanding of color phenomena. The authors also provide a useful summary of the main ideas that children typically hold about color formation, as shown in Table 1.

This work highlights the importance of considering students' prior conceptions when designing effective teaching strategies in the field of science education. By providing a new model for teaching color addition and demonstrating its effectiveness, this study contributes to the ongoing effort to improve science education practices.

Studies on the formation of colors have been developed in different contexts, with diverse methodological approaches, and under different theoretical frameworks. Some studies have focused on children's conceptions, while others have focused on undergraduate students. Moreover, some studies have used interviews or questionnaires, while others have used practical activities or experiments to investigate these concepts. This diversity of approaches and subjects is an indication of the complexity of the process of conceptualization and the importance of understanding how individuals build their knowledge about these fundamental physical phenomena.

Table 1
Children's conceptions about color formation.

Children's Ideas about Color Formation
Color is an intrinsic property of objects
Color is a result of lighting conditions
Color is a mixture of other colors
Color is a product of reflection or absorption of light
Color is a combination of light and dark shades
Colors are associated with emotions or sensations

[1](Ref. (Castro & Rodriguez, 2014)).

The present study contributes to the ongoing recherche on the development of children's cognitive abilities with respect to their understanding of colors. Specifically, this work advances the discussion in three keyways.

Firstly, this study proposes a psychological analysis of the children's verbal utterances using the Theory of Conceptual Fields. By applying this theory to the analysis of children's enunciations, this study aims to provide a deeper understanding of the cognitive processes underlying their understanding of colors.

Secondly, the research methodology employed in this study privileges the participation of the collective of students and their verbal exchanges. Situations are proposed for the children to solve, which encourages their active participation and engagement. This methodology allows for a more holistic view of the children's understanding of colors, as it considers the dynamic nature of their verbal exchanges and interactions with one another. In this case, the central point of our methodology is to create a situation of potential cognitive conflict for the research subjects. Using an LED projector, we mixed the colors blue, green, and red to produce white. Then, we asked the children to use only three colored pencils, in the same colors as the projected lights, to reproduce on a white sheet the result that had been projected. The result of the children's productions leads to a contradiction because the more they color, the darker the drawing becomes. At this moment, we propose to the children to find a solution to accomplish this task.

Finally, this study is part of a longitudinal research project, which involves subjects from different age groups. This approach allows for a genetic analysis of the children's notions of colors over time. By tracking the development of their concepts and language use, this longitudinal study aims to provide insights into the cognitive processes underlying their understanding of colors formation.

Taken together, these contributions provide a more comprehensive understanding of the development of children's cognitive abilities with respect to their understanding of colors. By using a psychological framework, privilege the participation of the collective of students, and adopting a longitudinal research approach, this study aims to advance the ongoing discourse on this topic.

2. Theory of conceptual fields

The theory of conceptual fields (TCF) was developed by Gérard Vergnaud, a French psychologist, to explain the complex nature of conceptualization and distinguish between predicative and operative forms of knowledge (Vergnaud, 1990). The theory draws inspiration from Piagetian perspectives and engages with sociocultural psychology, particularly regarding the notion of concepts as cultural tools always used in specific situations.

In Vergnaud's work, it is emphasized that concepts cannot be studied or understood in isolation or in a short period. Instead, concepts are interconnected within networks known as conceptual fields and are constructed by individuals over extended periods of time (Carvalho, 2013).

To account for the cognitive process of individuals, Vergnaud (Vergnaud et al., 2002) introduced the concept of scheme as an invariant organization of activity for a given class of situations. Schemes evolve from an early age, shaped by the myriad of situations that individuals face (Carvalho & Parrat-Dayan, 2015). There are four dimensions that constitute a scheme (Vergnaud et al., 2009): (1) rules of action and control that guide data collection and processing and indicate the need for action repetition, (2) goals and sub-goals that recognize what should be accomplished through the action, (3) possibilities of inference, which differentiate schemes from mere algorithms, and (4) operational invariants.

In addition, Vergnaud presents a specific formulation for concepts that is linked to a cultural dimension, consisting of three inseparable dimensions: (1) situations, where the operability of concepts is based on tasks recognized by the subject as something that must be faced and solved; (2) representations, such as verbal, written, and pictorial forms, that refer to a concept; and (3) operational invariants.

Operational invariants, according to the scheme definition, represent the part associated with the knowledge used to account for a situation. From the perspective of concepts that can be used by a subject to solve situations, operative invariants represent culturally available knowledge, also referred to as "knowledge-in-action" (Vergnaud, 1990).

Therefore, operational invariants play an important role in all actions of subjects. Through them, a subject recognizes some concepts as pertinent to constructing a satisfactory solution. These concepts, considered pertinent in action, are referred to as "concepts-in-action" in TCF. In each situation, a subject formulates propositions, building relations between concepts-in-action. These propositions are taken as true by the subject and will enable the resolution of the situation. These propositions are referred to as "theorems-in-action" (Carvalho, 2013).

For instance, Mota and Santos (Mota et al., 2018) identify the conception that the "mixture of lights follows the same rule as the mixture of paints." This conception can be unfolded into two complementary and indissoluble instances, concepts-in-action and theorems-in-action, in the light of the Theory of Conceptual Fields.

Implicitly, the concepts of color, composition, light, and pigment are used as the foundations for constructing explanations about the mixtures of lights and paints. These concepts, which guide actions and predictions about practical situations, are referred to as concepts-in-action. A proposition built with these concepts is the theorem-in-action.

To generalize, the concepts-in-action and theorems-in-action are referred to as operative invariants. These operational invariants are implicit during actions and evolve as subjects encounter increasingly complex situations of the same type. They are not scientific concepts or theorems since they cannot be proven or explained. However, they can evolve over time and approach scientific formulations.

Therefore, we suggest that conceptualization in science is a complex process that involves quantitatively and qualitatively increasing the operative invariants of subjects using science's concepts and relations as a reference. The operational invariants can be seen as the link between the domains of schemes and concepts. As a result, we advocate that research on conceptualization from the TCF perspective should begin with an investigation of the operative invariants used by subjects while performing tasks that challenge them.

3. Materials and methods

3.1. Subjects and contexts

The study was conducted in a highly regarded school located in a small city in Brazil, catering to urban children and adolescents. The research targeted students in their third year of elementary school, with an average age of 9 years old. The school has four third-year classes, each accommodating 25 students. For the study, three classes were selected randomly, based on the school's availability. The classes are taught by dedicated teachers who teach Portuguese, Mathematics, Natural Sciences, and Humanities, with a specialized Arts teacher for the classes. The children in the selected classes showed great enthusiasm and willingness to participate in the study. The research intervention was negotiated with the school's management and pedagogical coordination, where the intervention plans, terms of clarification, and free consent were presented. It was agreed that the activities would take approximately 60 min per class. Four researchers from our research group and two Pedagogy students participated in the study, with the lead researcher conducting demonstrations and questioning the children.

Due to the determination of the municipal education department, we were only allowed to make audio recordings of the activities. Each researcher positioned themselves in different places in the classroom and made audio recordings, as well as taking notes in their field notebooks.

3.2. Data construction process

The children were identified by numbers according to the place they were seated and received sheets of A4 paper with their respective printed numbers.

In addition to verbal interaction, we requested a final record of the activities. Each child received three colored pencils - one blue, one red, and one green - and a numbered blank sheet to record their productions. We used the same materials in each research section to perform the empirical demonstrations and collect the data, including a Newtonian disk with six circular sectors, a LED projector able to project lights blue, green and red, and opaque objects for shadow production.

We began with a conversation with the class to explain the purpose of the activities and to create an environment in which all children could feel free to express their ideas without worrying about being right or wrong. We then talked about colors, asking the children about their color preferences and whether they had seen rainbows before. The goal of this initial moment was to introduce the experiments on the formation of colors. All activities were carried out in a darkened classroom, and the sequence of activities applied in the three classes is presented below, along with their objectives.

3.2.1. Activity 1: Newton's disk

We conducted an experiment using a cardboard disc pierced in its center by a pencil and painted with six colors (red, orange, yellow, green, blue, and violet). By spinning the disc quickly, the resulting lights from each sector blended, giving the illusion of seeing white. We then conducted the color fusion experiment and asked the children to explain the reason for the change in color sensation.

Next, we used the projector to illuminate Newton's disc with only red light and asked the children to explain the change in view. We wanted to start a discussion about the difference between what we see in white light and what can change when monochromatic light falls on objects. By doing so, we created a situation that highlighted the difference between how the same object is seen when illuminated by different light sources.

3.2.2. Activity 2: monochrome light projection

For the second activity, we used the red-light projector to cast a red light onto the white ceiling. The initial goal was to continue the discussion about the use of monochromatic light to illuminate objects. Next, we wanted to introduce the idea that an opaque object can block the passage of light and create a dark shadow. The explanation that a dark shadow appears when an opaque body prevents the passage of light is easy to understand and was well-received by the children. While this stage of the activity was not designed with a direct research interest, its goal was to set the stage for a more unusual situation: projecting colored shadows.

3.2.3. Activity 3: mixing colors two by two and projecting colored shadows

In the third step, we used the projector to project yellow by activating red and green lights, magenta by activating red and blue lights, and cyan by activating green and blue lights. We showed the children the lights used for each case and then turned the projector to the ceiling. Next, we placed an opaque object such as the researcher's hand or a white sheet in front of the projector, causing a dark shadow to appear in the center and two colored shadows, each with one of the colors of the lights. For instance, when the red and blue lights were used, a dark shadow appeared in the center with two additional shadows - one red and the other blue - as shown in Fig. 1.

Before the shadows were formed, we asked the children what they thought would happen if they placed their hand in front of the projector. They predicted that a dark shadow would appear, just like what they had

Fig. 1. Projection of colored shadows using the red and blue fonts. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

seen before with monochromatic light. Our goal was to present an unusual situation that would generate cognitive dissonance, where the children's expectations were challenged.

3.2.4. Activity 4: use of the three colors together and projection of colored shadows

In the last step, we used three colors together (blue, green and red) to form white light. We then asked the children what would happen if we placed a hand in front of the projector. Initially, the children thought that only the primary colors would be present in the shadows. However, when we performed the experiment, they were surprised to see that the shadows were not only red, green, and blue, but also yellow, cyan, and magenta. This unexpected result caused cognitive imbalance in the children as they realized that what they were seeing exceeded their initial predictions.

3.2.5. Activity 5: record and explanation

After completing the activities, the children were provided with three colored pencils (red, blue, and green) and a numbered sheet to reproduce the last color mixing experiment. They were instructed to draw the color mix created with the projector using the provided pencils, and given the freedom to add any other drawings or relevant information. Some children attempted to mix colors two by two, as done in activity 3, while others aimed to produce white by using all three pencils.

The purpose of this exercise was to present a contradiction between the colors generated by the researcher's three colored lights and the children's production using the three colored pencils, and to assess whether the children could recognize and resolve this contradiction. We aimed to obtain empirical data that could help us infer the cognitive processes used by the children.

To further understand the reasoning behind their actions, we conducted a discussion with the children. Subsequently, each child was asked to write an explanation of the difference between the designed experiment and their drawing. These explanations were collected, digitized, and analyzed by the research group. The Materials and Methods should be described with sufficient details to allow others to replicate and build on the published results. Please note that the publication of your manuscript implies that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited.

4. Results

The process of interpreting research data began with three meetings of the research group, during which each member shared their impressions of the activities performed and highlighted the points they considered most relevant in the children's productions.

To infer the operative invariants used by the children, we used a content analysis model based on Bardin's approach (Bardin, 1977). This method helped us to identify the underlying meanings in the children's task performance.

Our pre-analysis involved reading the written productions of all the children and listening to the audio recordings of their interventions. We then made notes on the most recurring response models to categorize the children's responses accordingly. We presented this first categorization effort to the research group to cross-reference the interpretations among the researchers involved in this project.

We separated the speech turns and the most representative written productions of each category and established acceptable differences between the answers for inclusion in the categories. Afterward, we checked the consistency between our initial analyses and the categories agreed upon among the researchers. We repeated this process of interpretation, category evaluation, and consistency verification two more times until we arrived at the categories presented later.

Through this process, we inferred three variables that indicated the operative invariants used by the children: (1) color as luminosity, (2) color composition dependent on the order in which colors were mixed, and (3) color as an intrinsic property of the object.

With the organization of the categories, we focused on the most frequent forms of interpretation of the experiment proposed in activity 4. This allowed us to identify the operative invariants and organize them to construct possible ways of how the children acted. Finally, we selected written texts, drawings, and speeches that were exemplary of these operative invariants identified to present in this article.

5. Discussion

The focus of our investigation will be on the activities 4 and 5, and for anonymity, we will identify the children using a six-digit code, linked by hyphens. The first two digits refer to the child's sheet number, the next two digits are the day of the survey, and the last two digits are the month of the survey.

During activities 2 to 4, the children and teachers interacted intensely with the researchers, presenting their explanations and concerns. We observed that the children often gave tautological explanations, which is common for their age group, where the logic of object attributes is decisive for constructing statements (Piaget & Garcia, 1987).

In the activity involving Newton's Disk, when the red light was thrown on the disk, and the researcher asked the reason for the change, the children indicated that it was because of the projector. When asked what the projector did to change the colors of the disc, the children said it used red light. The researcher then reinforced the question, asking why the perceived colors were different when the projector was turned on. The children's answers can be summarized by the statement made by a child, which indicates an advance in their reasoning.

(12-31-10): "When you put on red light, the red is stronger … the yellow is weaker …

This type of statement implies that the projector is "stronger" than the disk and, in a way, "imposes" its color on the yellow sector of the disk. Based on this statement and others researches in this field (Feher & Rice, 1987; Guesne et al., 1985; Viennot, 2002), we can infer that children believe that the perceived color of Newton's Disk is a property of the disk and not the result of the interaction between the object and the light that illuminates it. However, this property can be changed if a "stronger" object produces such a change.

We observed that the explanations provided by the children often followed a linear logic, without considering the relationship of cause and effect. Many children attributed the colors of the shadows to the colors of the lights used in the projector, without fully understanding the underlying principles of color mixing and shadow formation.

In the following episodes, we will present some of the most representative written productions and drawings that best illustrate the identified operational invariants. Of the 63 children whose productions were evaluated, 56 children (89%) attributed the differences between the projected and drawn images to the differences between the objects used (pencil and projector). The other 7 children (11%) presented explanations linked to the characteristics of the leaf, the decomposition of colors, the wood, or did not present any answers.

Within the "difference between pencil and projector" category, the answers were not uniform. The largest subcategory, with 32 children (51%), explicitly indicates that the projector is a "lighter" object than the pencil and, therefore, can produce white. In contrast, the pencil, being darker, can only produce dark shades.

Let's present a child's creation that illustrates this concept in Fig. 2.

In the figure, the child writes that the difference between the white created by the projector and the result of coloring is "because of the brightness, but if you color it lightly, I think it'll work." The first coloring the child did is on the left side of the figure. Then, after writing the aforementioned sentence, the child attempts to color two more times, reducing the pressure applied to the sheet.

In the same category, child 05-29-10 starts their coloring by applying strong pressure to the pencil, as can be seen in Fig. 3A. Upon realizing that the result was too dark, this child attempts to color with lighter pressure, as shown in Fig. 3B. After being unable to achieve the expected result, the child states that the difference occurs "because the pencil is darker".

Subsequently, we can examine additional comparable explanations.

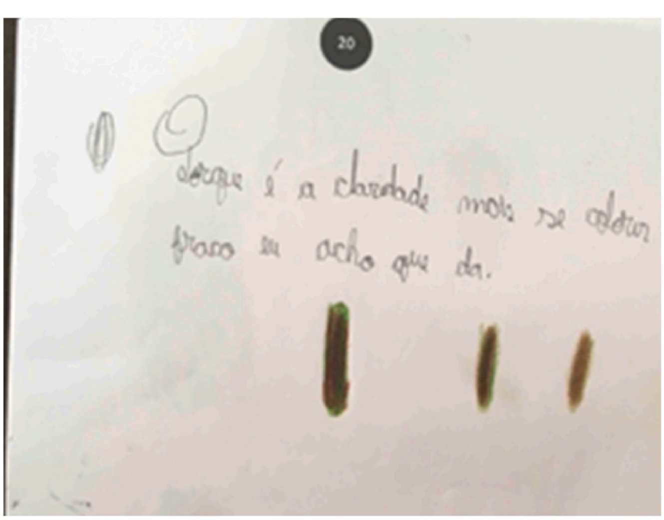


Fig. 2. Written production of the student 20-31-10.

(A) (B)

Fig. 3. Written production of the student 05-29-10.

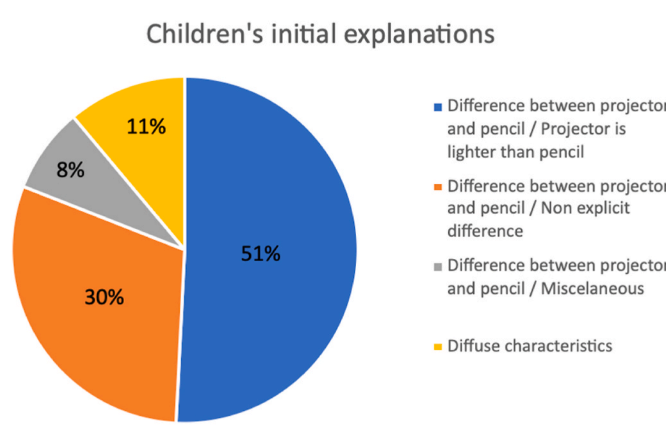
(12-31-10): "When you put red light, red is strong … the yellow is weaker …
(10-01-11): "light is stronger than pencils"
(01-01-11): "because the light is strong and the color of the pencil is weak"
(15-01-11): "because light is stronger than pencils"
(09-29-10): "because it is a light that gives clarity and in pencil it does not give"

There is also a group that acknowledges the differences between the pencil and the projector, without explicitly identifying clarity as a factor that differentiates them. In this subcategory, there are 19 children (30%).

(04-01-11): « in the colors of pencils … it isn't possible. There's something different there on your <<projecto>> »
(06-29-10): « because the light forms itself alone and we cannot do this »
(03-29-10): "The light has a different tone"

The remaining two subcategories are sparsely populated. In one subgroup, three children assert that the projector produces darker colors than the pencil. In the second subgroup, two children contend that the projector is capable of blending colors, whereas the pencil is not.

The following chart summarizes these initial explanations from the children.



Despite the variations, there is a common thread in the way children approach problem-solving, and this is linked to the function of operational invariants. When presented with a problem, a subject will use relevant concepts-in-action to come up with a solution. If the solution is satisfactory, the subject will consider it resolved. However, if the result is not what they expect, they will look for other operative invariants to explain the problem.

When the students were asked to reproduce the projection of the three colors using only three colored pencils, they used a random order to color the sheet with the expectation that the mixture of the three colors would result in white. At that moment, there was no problem to be solved, given that the three colors of the pencils were exactly the three seen on the projector. In other words, it was merely a straightforward reproduction.

The problem arose when the coloring done by the children did not result in the production of white. From that point on, two distinct concepts-in-action were predominantly employed by the children.

The first, used by 35 children, was the order in which they colored, with the consequent theorem-in-action: "there is a correct order of coloring that produces white." This way of acting led children, regardless of the final explanation produced, to attempt coloring using different orders (though not systematically) in the hope that one of them would lead to white. This conception may be linked to the idea that each color can suppress a certain amount of light, and that there is a correct order in which such suppression is minimized, leading to white. In other words, it constitutes a more complex organization that can contribute to the construction of the concept of light absorption, a scientific concept relevant to explaining the proposed situation. This somewhat vague and incomplete idea was also found in another study on the same subject that, however, used younger children as research subjects (Carvalho & Souza, 2017).

However, the failure to reproduce what had been seen motivated the children to search for other concepts deemed relevant. Among the 35 children, 16, in addition to 7 others who had not explicitly mentioned the order as determinative, reiterated that the pressure applied during coloring could be a pertinent concept to explain the difference between the results of the projector and the pencils. The theorem-in-action "the lighter the pressure exerted while coloring, the clearer the drawing becomes" and "the clearer the drawing, the closer it will get to white" are acknowledged as true at this point. These children then created additional drawings, coloring the sheet with light pressure, in the hope of achieving white. In this case, the failure to accomplish the task caused frustration for the children.

In Fig. 4, it is possible to observe the sequence of attempts by a child to produce white using the three colored pencils.

In Fig. 4, the numbers indicate stages of the production of the drawings. In the beginning, the child colored strongly in two distinct orders, being that in (1) the last color was blue and in (2) it was green. In part (3), the child has already tried to color with less pressure and was thus decreasing in parts (4) and (5).

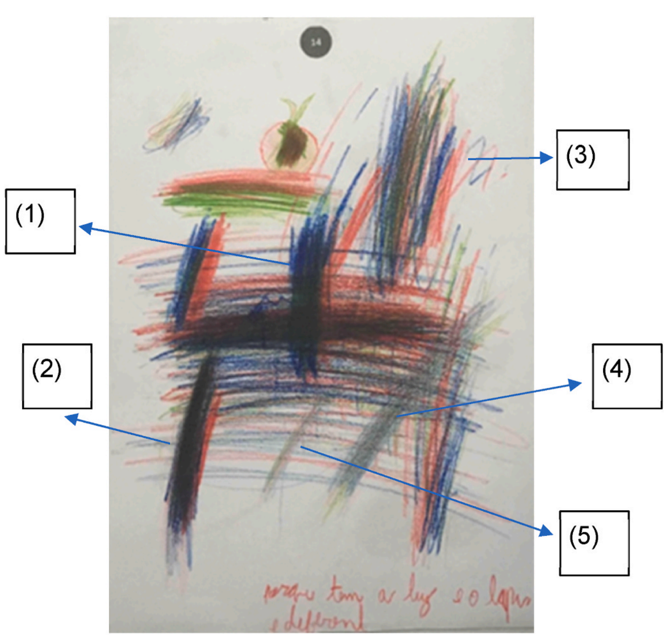


Fig. 4. Written production of the student 14-29-10.

Some of these children tried other possibilities, still linked to the concept in action of clarity. Some children explained that if it was colored with pencils, or if other lighter colored pencils or more "wet" elements were used, the result would be white.

> (10-01-11): « … What if we try to felt-tip pen? ≪After we allowed her to use the mugs ≫ It didn't work, I gave black."

For several children, the explanation of clarity found an empirical referent associated with the projector, which was the only element that, in fact, generated the white. The curious thing is that even though we were not able to produce the white with pencils or pencils, the explanation linked to the clarity seems to have been satisfactory for the children, because they continued to say that the projector was lighter than the pencils. This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

6. Conclusions

Our study aimed to identify the operational invariants that children use to resolve conflicts related to color formation. These findings will aid in constructing a genetic analysis of this area, given that our longitudinal study is ongoing. We found a strong correlation between our results and those of previous research, despite differences in methodology and sample size.

We observed that children attribute differences between projected light and their drawings to the clarity of the projector, a property they do not find in pencils. This suggests that children use a theorem-in-action like this: « colors are distinct intensities of darkness », something that aligns with the findings of Feher and Meyer (Feher & Meyer, 1992) and Castro and Rodriguez (Castro & Rodriguez, 2014). Some children even believed that using felt pen could produce white, as they considered this object is lighter than the pencil. While this is conceptually inconsistent since both pens and pencils belong to the color-pigment set, we interpret it as a principle in the construction of the concept of absorption, which explains the proposed situation.

Another common theorem-in-action among children is that « color is an inherent property of objects », regardless of how they are illuminated. This reflects the logic of attributes, which is common at this age (Piaget, 1967). We don't know yet if this theorem-in-action will persist in teenagers and adults.

Our research enriches this discourse by delving into the psychological mechanisms employed by children as they engage in problem-solving, redirect explanations, and make predictions based on their actions. This endeavor involves identifying operational invariants, a critical activity that not only facilitates the construction of a descriptive framework but, more importantly, provides explanatory power during the ongoing conceptualization process.

The explanatory prowess of our findings takes on a more nuanced role when focused on a specific age group, as it refrains from establishing a deterministic genetic lineage for the formation and evolution of these invariants over an extended period. Despite being confined to a particular age group, our results carry immediate implications for classroom settings, informing the development of didactic interventions in this subject.

By positioning our research alongside studies involving diverse audiences across various age groups, we aim to offer a comprehensive understanding of the primary trajectories that the conceptualization process may follow.

In this context, we've discerned a significant pathway associated with the concept of absorption among children aged 4–5 and those examined in the present study. Specifically, there is a prevailing notion that different pigments "obstruct" portions of light, resulting in their mixtures yielding a notably dark color.

Looking ahead, we anticipate that further research involving adolescents and adults, encompassing both educational and non-educational settings, will allow us to construct a more expansive framework elucidating the evolution of operational invariants and their contributions to the conceptualization process.

This research, as presented, can serve as a foundational resource for scholars in the field of science education seeking Theory of Conceptual Fields support in their investigations. It delineates the fundamental tenets of this theory and its relevance for the field, fostering a deeper understanding of the processes at play.

CRediT authorship contribution statement

Gabriel Dias de Carvalho Junior: Writing – original draft, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Andressa Xavier Zinato de Carvalho:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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