

Changes to equipotential diagrams to improve student ranking of electric potential

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Student issues with understanding electric potential and interpreting diagrams were explored in a prior study. The prior study showed equipotential diagram modifications of line thickness and color significantly increased student gaze times at the diagrams without increasing correctness. Students' inattention to electric charge sign and its role in electric potential was a major issue. This study implemented further modifications, based on theories of visual attention and affordance, to electric potential diagrams to increase visual salience of charge sign. Students ranked electric potentials for points on traditional or modified diagrams. Pre- and posttest comparisons and interview results showed training with modified diagrams produced correctness gains of 21% compared with gains of 11% for training with traditional diagrams, and improvement of 36% in application of a conditional rule including charge sign compared with the prior study. In-person training combined with modified diagrams yielded highest pre to post gains of 27%.

I. INTRODUCTION

This study presents the results of an investigation into the effects of modifications of traditional equipotential diagrams on students' ability to correctly understand the modified diagrams. Students' ability to interpret and apply the equipotential diagrams and their understanding of the electric potential was assessed by their proficiency at ranking the electric potential values for selected points in equipotential diagrams. The diagrams were modified with color and symbols, based on theories of visual affordances and grounded cognition. Quantitative and qualitative response data, and the effects of two comparative trainings, are presented to explain the specific issues students have with interpreting equipotential diagrams for point charges.

Electric potential is a widely used concept that students have a variety of difficulties with. These issues have been well explored and include issues with electrical potential energy, relating the electric potential to the electric field, and connecting electric potential and current flow [1–3]. Other common difficulties involve assigning electric potential for conductors, the choice of the zero point [4], and the importance of charge sign in determining the electric potential [5].

Equipotential diagrams are one representation of the electric potential. There has been extensive research on student difficulties with interpreting and applying data from pictorial and graphical sources such as free-body diagrams and motion maps [6, 7], however, there has been relatively little research on student issues with equipotential diagrams. Two such studies on equipotential diagrams were reported in the 2013 and 2018 PERC Proceedings [5, 8].

In this investigation the authors applied theory of visual affordances and grounded cognition theory in designing equipotential diagrams that best aided students in correctly applying the concept of electric potential. Grounded cognition states that perceptual symbols, created by a sensory-motor system during perception, are the fundamental units the brain uses to construct a concept. When we think about an abstract concept such as a chair our perceptual system activates symbols which to help us mentally create the concept of chair [9, 10]. Visual affordances are features or properties of a diagram or image that shows how it may be used [11]. This means that the features of a diagram relevant to the purpose of the diagram should be visually salient in a way that supports a correct physical understanding.

A prior study with modified equipotential diagrams found that students pay increased attention to the enhanced features of the diagram, but do not have an improved correctness rate of ranking the electric potential, partly because they do not take into account the charge sign [5]. The study used colors in the diagrams (blue for positive, red for negative), changes in color intensity, and variations in equipotential line thickness, in addition to conventional proximity to sources of charge to indicate charge sign and electric potential. This study incorporates different changes to equipotential diagrams designed so students will focus more on the sign of the charge.

The color variations were retained, but a constant equipotential line thickness was used. Electric charge sign is emphasized by larger charge symbols and markings on the negative equipotential lines. The new changes were incorporated to provide additional visual cues for the charge sign and highlight its effect on potential. The results from this study will be compared with the previous study as a measure of the effectiveness of the changes to the diagrams. This will enable development of a more effective curriculum for teaching electric potential.

II. METHODOLOGY

The data were collected during two two-week periods in a traditionally taught algebra-based physics class at a medium-size Midwestern university. This followed instruction of the class on electric charge, electric fields, and electric potential. The class was predominately composed of life science majors in their junior year and was 54% female. There were 68 students with a 95% participation rate in the research.

Data was collected from the class as a participation-graded laboratory activity. Half the class took part in 50 minute in-person sessions during the students' laboratory periods. The diagrams and questions were presented to each student via individual PowerPoint presentations. Each slide had an equipotential diagram (see Figure 1 for examples) with a question asking the student to rank the potential between two points. Each student recorded the answers to potential ranking questions on a Scantron form. Midway through the semester there was a transition to online classes and the instruments were converted to online surveys which used identical images and questions.

Students taking part in these sessions were randomly assigned to complete one of two conditions. The conditions, A and B, were two matched sets of pretest, training, and posttest questions. The task for both conditions was for students to correctly rank the electric potentials between two points indicated on the diagrams. Equipotential diagrams were created for a variety of positive and negative electric charge arrangements. These charge arrangements included individual charges, two charges of the same sign and magnitude, two charges of the same sign and different magnitudes, and two charges of opposite signs and equal magnitude. The points selected for ranking on each diagram comprised points on the same equipotential line (both close to each other and far apart), points close to the same charge but on different lines, and points on different lines and adjacent to different charges. This yielded 66 different diagrams with associated ranking questions - 33 traditional black and white diagrams and 33 diagrams modified by color and line modifications.

Condition A gave students 33 questions with modified diagrams followed by 33 questions with traditionally drawn diagrams. Students then received a short training with 11 modified diagrams where students were given feedback on the correct answers. After this, students completed a set of 33

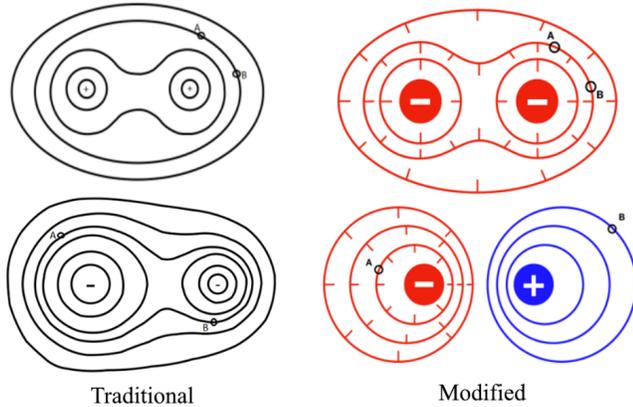


FIG. 1. Examples of traditional and modified equipotential diagrams presented to students.

posttest items about the traditionally drawn diagrams. Condition B gave students 33 questions about traditional diagrams and then gave students 33 questions about modified diagrams. Students then received a short training using 11 traditional diagrams by giving students feedback on the correct answers for the items. Students then completed a set of 33 posttest items with the traditionally drawn diagrams which was identical to that of condition A.

III. FINDINGS

A. Pretest comparisons and discussion of item difficulties

A 2018 study in the same course [5] on the effects of modified vs. traditionally drawn equipotential diagrams found that, combining data from both conditions, the mean correctness rates were 59% correct on the traditional diagrams and 63% correct on the modified diagrams, and were 61% correct on the first set of questions and 63% correct on the second set. Students presented with traditional diagrams first, followed by modified diagrams did 9% better on the second set of diagrams. If the modified diagrams were presented first, the improvement was 6%.

The predominant findings of the prior study were that modification to the equipotential diagrams resulted in increased gaze time, and that the increased gaze times did not result in increased correctness rates. Students neglected the sign of the charge in their responses and followed a “closer is higher electric potential” rule 78% of the time regardless of the sign of the charge [5].

Because of these findings the present study chose to revise modifications to equipotential diagrams in a manner that emphasized the charge sign: retaining the color differences between positive and negative, increasing the size of the charge symbols, and adding tick marks to equipotential lines around negative charges, oriented in the direction of decreasing electric potential. Changes in line thickness with potential change

TABLE I. Percent of students responding correctly to ranking questions on pretest by diagram type, charge sign and presentation order

Condition A (N = 31)					
Order	Diagram	Negative	Positive	Same Line	Total
First 33	Modified	38%	59%	81%	60%
Second 33	Traditional	42%	54%	85%	62%
Condition B (N = 28)					
Order	Diagram	Negative	Positive	Same Line	Total
First 33	Traditional	50%	68%	81%	66%
Second 33	Modified	47%	70%	78%	65%

were removed.

The overall pretest scores for the new diagrams are listed in Table I by diagram, question set order, and charge sign for conditions A and B. Combining the data for both conditions the overall pretest correctness rates were 64% on the traditional diagrams and 62.5% on the modified diagrams, and 63% on the first set of 33 questions and 63.5% on the second set of 33 questions. A two-way ANOVA showed that there was no main effect due to either the type of diagram (traditional or modified) or the order in which the question sets were presented (traditional diagrams first or modified diagrams first), nor was there an interaction effect between diagram type and order. These results are very similar to the pretest results of 2018.

In addition to overall pretest score, an analysis of individual items showed that students did very well at ranking electrical potential between two points that were on the same line, selecting “equal potential” 81% of the time. Students also performed much better in ranking the potential between two points for positive charges than for negative charges. The mean correctness rate for items with positive charges was 63%, while the correctness rate for items with negative charges was 44%. A t-test showed these were significantly different ($t = 4.224$, $p = 0.000$). Further analysis showed the closer point was chosen as higher potential 42% of the time regardless of charge sign. This is consistent with the combined rules of “same line is equal potential” and “closer is higher potential”.

In the prior study the correctness rate for items with positive charges was 90% and the correctness rate for items with negative charges was only 17%. Analysis showed the closer point was chosen as higher potential 78% of the time. Comparing the 42% to the 78%, 36% more students used a conditional rule including charge sign in ranking electric potential. This demonstrates a much higher rate of attending to the charge sign with the new diagrams. The modifications to the diagrams were designed to help students correctly apply concepts that points closer to charges had potential of greater magnitude and that the sign of the charge affects whether the potential is positive or negative. This result shows that the new features incorporated into the modified equipotential diagrams created greater attention to the sign of the charge.

B. Results of brief feedback based training

There was a training session included in each condition, designed to reacquaint students with equipotential diagrams and introduce them to the modified colors and symbols. After completing the modified and traditional question sets of the pretest, students were given a short training activity. The activity consisted of 11 diagrams. After entering their ranking of the electric potential for each diagram students were given the correct answer. For Condition A the training was with modified diagrams, and for Condition B the training was with traditional diagrams. Following the training, both groups of students completed a posttest with 33 traditionally drawn diagrams. Both types of diagram were used in the training to observe the utility of the modified diagrams for instruction. Traditional diagrams will be seen most often in practice.

A dependent-samples t-test with modified diagram training showed significant pre to post gains in mean correctness rate of 21% ($t = 5.589$ $p = 0.000$). A dependent-samples t-test with traditional diagram training showed significant pre to post gains in mean correctness rate of 11% ($t = 2.340$ $p = 0.027$). The difference between the mean gains of 9% was not significant ($t = 1.502$ $p = 0.139$). Cohen's d was 0.340, showing a medium effect size and suggesting that with a larger sample the difference might be significant. The previous study had a pre to post gain of 10%. The increase in pre-post gain over that obtained in the previous study is indicative of improved performance with the new modifications to the equipotential diagrams.

Overall, pre to post scores showed a good gain with training: 21% with the new modified diagrams compared with 10% for modified diagrams from the previous study. Gains in correctness for items with negative charges shows a gain of 35% for training with the modified diagrams compared with 26% for training with traditional diagrams. Items with positive charges had gains of 23% for modified diagrams compared with 8% for traditional diagrams. With the original form of modified diagrams there was a drop in correctness rate for items with positive charges, whereas with the new version of modified equipotential diagrams there were gains in correctness on items both with negative and positive charges. This makes it clear that the training with the new designs of modified diagrams had the effect of getting some students to use a conditional rule including the sign of the charge. After the training, 38% of students consistently responded with the correct rule, compared with 30% from the prior study. An additional 21% (vs. 26% from the earlier study) of students responded with the correct rule most of the time.

C. Interview results

Following completion of the in-person ranking tasks in Condition A or Condition B nine students were given a semistructured interview consisting of ten questions covering

TABLE II. Pre-post correctness scores for only traditional diagrams

Condition A: Modified Diagram Training (N = 31)				
Item Description	Negative	Positive	Same Line	Total
Pretest Average	42%	54%	85%	62%
Posttest Average	77%	77%	91%	83%
Condition B: Traditional Diagram Training (N = 28)				
Item Description	Negative	Positive	Same Line	Total
Pretest Average	50%	68%	81%	66%
Posttest Average	76%	76%	79%	77%

electric potential, equipotential diagrams, and visual representation of the electric potential. Each interview took about 20 minutes to complete. The interviews were intended to investigate students' perception and attitudes about the electric potential, how it could best be represented visually, how students got information from equipotential diagrams, and the modifications to traditional equipotential diagrams. Examples of some of the questions are: "How do you define the electric potential?"; "How would you visually represent electric charges, electric fields, and electric potential?"; "When you rank the electric potential based on a diagram, what clues do you look for?"; and "Did you prefer the traditional diagrams or the modified diagrams?". Three main themes are highlighted here: students preferred the modified diagrams; students realized charge sign was important; and students strongly associated distance with electric potential.

The results from the interviews were that 67% of the students preferred the modified diagrams with color, larger charge sign indicators, and markings indicating negative potential. Some interview quotes about the modified diagrams were: "*liked the color with line markers*"; "*(color) made it easier to distinguish sign of charge*"; and "*tick marks helped identify charge sign*". 78% made a statement that color helped in determining the sign and potential. 33% found tick marks helpful while 22% did not understand the purpose of the tick marks.

In the prior study students did not observe the charge sign, or thought it unimportant in determining electric potential. 67% of the students stated that charge sign was one of the features used in ranking potential, and 89% specified distance from a charge important in determining potential.

Student comments about the rules for determining of ranking potential were: "*After training - closer to positive charge is higher potential*"; "*Look at positive or negative charge and how close it (ranking point) is to that*"; and "*Distance from positive charge...distance from negative charge*". One student said that the electric potential depended on the distance from the negative charge.

It is notable that 22% of the students envisioned an electric potential diagram as an image with arrows pointing away from a charge: the standard diagram used to portray the electric field. "*Positive point, negative point. Arrows pointing from positive to negative*".

TABLE III. Percent of students responding correctly to ranking questions on pretest by diagram type, order of presentation, and in-person or online assessment

In-Person Condition A (N = 17)					
Order	Diagram	Negative	Positive	Same Line	Total
First 33	Modified	27%	59%	77%	55%
Second 33	Traditional	30%	51%	83%	56%
In-Person Condition B (N = 13)					
Order	Diagram	Negative	Positive	Same Line	Total
First 33	Traditional	48%	64%	85%	65%
Second 33	Modified	43%	72%	78%	64%
Online Condition A (N = 17)					
Order	Diagram	Negative	Positive	Same Line	Total
First 33	Modified	47%	60%	84%	64%
Second 33	Traditional	52%	57%	87%	66%
Online Condition B (N = 13)					
Order	Diagram	Negative	Positive	Same Line	Total
First 33	Traditional	52%	73%	77%	67%
Second 33	Modified	53%	68%	78%	67%

D. Effects of online learning

In the middle of the semester the university transitioned from a traditional lecture-based in-person classroom setting to online instruction. The method of data collection changed from an in-person venue where data was collected via computer in a laboratory environment to an entirely online setting where data was collected through a web-based survey. The same diagrams and questions were used in the same order, only the students responded through the survey software. Neither assessment was timed.

The pretest scores separated by in-person and online participation are listed in Tables III and IV by diagram type and item set order for conditions A and B. For the in-person data the overall pretest correctness rates were 64% on the traditional diagrams and 62.5% on the modified diagrams, and 63% on the first set of 33 questions and 63.5% on the second set of 33 questions. There is no significant difference between the combined mean correctness rates of 60% for in-person participants and 66% for online.

Comparisons of in-person and online pre- and posttest scores for traditional diagrams are given in Tables III and IV. The mean overall gain across both trainings for in-person testing was 22%. The mean overall gain across both trainings for online testing was 12%. These means were not quite statistically different ($t = 1.699$, $p = 0.095$). This points to better gains for students working in-person than online.

The combined effects of training with the modified diagrams and online assessment are substantial. For training with modified diagrams the in-person gain in correctness testing with traditional diagrams was 27%. For training with traditional diagrams the online gain in correctness testing with traditional diagram was only 5%. The difference is signifi-

TABLE IV. Pre-post correctness scores for only traditional diagrams, sorted by in-person or online assessment

In-Person Condition A: Modified Diagram Training (N = 17)				
Item Description	Negative	Positive	Same Line	Total
Pretest Average	30%	51%	83%	56%
Posttest Average	77%	74%	94%	83%
In-Person Condition B: Traditional Diagram Training (N = 13)				
Item Description	Negative	Positive	Same Line	Total
Pretest Average	48%	64%	85%	65%
Posttest Average	80%	77%	90%	82%
Online Condition A: Modified Diagram Training (N = 17)				
Item Description	Negative	Positive	Same Line	Total
Pretest Average	52%	57%	87%	66%
Posttest Average	77%	80%	89%	83%
Online Condition B: Traditional Diagram Training (N = 13)				
Item Description	Negative	Positive	Same Line	Total
Pretest Average	52%	73%	77%	67%
Posttest Average	72%	75%	65%	72%

cant ($t = 2.415$, $p = 0.023$) and implies that these modified diagrams are better for instruction, especially when combined with in-person teaching.

IV. CONCLUSION

This was a study investigating students' understanding of electric potential and their ability to interpret and use equipotential diagrams. The study builds on a previous study of modified equipotential diagrams. There are three main results of the study.

With new modifications introduced to equipotential diagrams involving color, increased charge symbol size, and features directing visual attention to the signs of charges, student correctness rates ranking electric potential were significantly improved. The modified diagrams combined with feedback-based training resulted in significantly improved student understanding and use of conditional rules when evaluating electric potential.

Interviews revealed students appreciated the modified equipotential diagrams and considered them easier to use than traditional black and white diagrams.

Online training and assessment appears to have been less effective than in-person training and assessment when using traditional diagrams. This has implications for transitioning to online learning.

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