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Distance and displacement inventory: Construction, validation and structural analysis

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Abstract: This research aims to develop an instrument for assessing understanding distance and displacement concepts. Distance and Displacement Inventory (DDI) is an instrument constructed in multi-representations, including picture, table, graphic, mathematical, and verbal representations. This instrument is in multiple-choice format with ten questions to assess students' understanding of distance traveled and displacement. DDI development refers to R&D design by Borg&Gall and test development flowchart by Beichner. DDI was applied to 357 students in Indonesia who had taken introductory physics courses. Student answers were analyzed to determine the DDI's psychometric properties and structural analysis. The analysis results show that the DDI is adequate for assessing students' understanding of travel distance and displacement concepts. Meanwhile, the structural analysis of students' knowledge results shows that students have different perceptions of each question item according to their representation. Furthermore, students who understand the concept of distance traveled and displacement in one representation may need help understanding it correctly in another representation. This research implies the necessity of designing learning designs based on multi-representations and teaching students about the changes between these representations.
Keywords: assessment; displacement; distances; kinematics; multi-representations

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Introduction

Distance and displacement concepts are primary and essential concepts in physics, especially in kinematics material. This has encouraged many researchers to reveal students' understanding of kinematics concepts (Jufriadi et al., 2023). Students' understanding of distance and displacement will influence their understanding of speed and acceleration. Students' knowledge of the basic concepts of kinematics will automatically affect their understanding of other related physics concepts. Information about students' understanding of concepts can be used to design learning designs that are good, effective, and appropriate to students' needs. One way to reveal students' conceptual understanding is to assess their conceptual understanding.

One of the assessment formats is an interview. Interviews can investigate students' understanding of concepts in detail. Interviews can reveal students' complex cognitive structures.

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However, the assessed sample size will be relatively small (Fuchs & Czarnocha, 2016; He & Schonlau, 2020; Kaltakci-Gurel et al., 2015, 2017; Schonlau et al., 2021; Young et al., 2018). Another area for improvement in the interview format assessment is that the analysis process is more complex, takes a long time, and requires good communication skills (Jufriadi et al., 2023). In further developments, the concept of understanding assessment that has been developed professionally is an assessment with a multiple-choice format. Assessment with a validated multiple-choice format effectively and efficiently assesses students' understanding of concepts. Apart from that, multiple-choice format assessments given before and after the learning process can measure a learning model's effectiveness despite several weaknesses (Brown & Singh, 2021). Several assessments that have been developed professionally with a multiple choice format include Mechanics Diagnostic Test, Mechanics Baseline Test, Force Concept Inventory, Test of Understanding Graphs in Kinematics, Force and Motion Conceptual Evaluation, Rotational and Rolling Motion Conceptual Survey, Force Velocity Acceleration, Test of Understanding of Vectors, Representational Competence in Kinematics, and Kinematics Concept Test (Barniol & Zavala, 2014; Beichner, 1994; Hestenes et al., 1992; Hestenes & Wells, 1992; Klein et al., 2017; Lichtenberger et al., 2017; Rimoldini & Singh, 2005; Rosenblatt & Heckler, 2011; Thornton & Sokoloff, 1998).

The Mechanics Diagnostic Test was constructed to assess speed and change of direction (Halloun & Hestenes, 1985), and the Mechanics Baseline Test to reveal students' understanding of the concepts of Constant acceleration, average acceleration, tangential and normal acceleration (Hestenes & Wells, 1992). Hestenes et al. developed the Force Concept Inventory to investigate position, velocity, changing speed, velocities vector, acceleration, and constant acceleration in a parabolic orbit (Hestenes et al., 1992). In its development, Beichner developed the Test of Understanding Graphs in Kinematics in graphical representation. This assessment is widely used to investigate understanding of kinematics concepts, namely velocity on the position-time graph, acceleration on the velocity-time graph, displacement on the velocity-time graph, change in velocity on the acceleration-time graph, determining another suitable graph on the kinematic graph, determining textual descriptions that match the kinematic graph, determining the graphic that matches the description of the textual movement (Beichner, 1994). Next, Lichtenberger et al. developed the Kinematics Concept Test to assess understanding kinematics concepts in multiple representations. Several kinematic concepts assessed include velocity as rate, 1D and 2D vector, displacement as area, acceleration as rate and 1D vector, and velocity change as area (Lichtenberger et al., 2017).

Although assessments to systematically assess the basic concepts of kinematics in multiple representations have been developed, such as the Kinematics Concept Test, assessments developed to explore the concepts of distance and displacement in complete representations (i.e., mathematical, graphical, pictorial, tabular, and visual representations) still do not exist. To complete the assessment of kinematics concepts that have been developed professionally, this research developed the Distance and Displacement Inventory (DDI). Developing DDI in five representations is very important to do. This will help educators evaluate students' understanding of distance and displacement comprehensively and more complexly. This research aims to develop a valid and reliable assessment to assess mastery of the concepts of distance and displacement.

Method

DDI development refers to the R&D design by Borg & Gall (Gall et al., 2007) and the test development flowchart suggested by Beichner (Beichner, 1994). Generally, the research stage begins with initial research and gathering information, followed by formulating objectives and test items. Next, DDI version 1 was developed based on the objectives and design of the test items. DDI version 1 was tested, reviewed, and revised to become version 2. DDI version 2 was improved to become DDI version 3, and DDI version 3 was refined to become the final version of DDI. The stages of DDI research and development are shown in Figure 1. Overall data was collected and analyzed from 357 students spread across 11 universities in Indonesia.

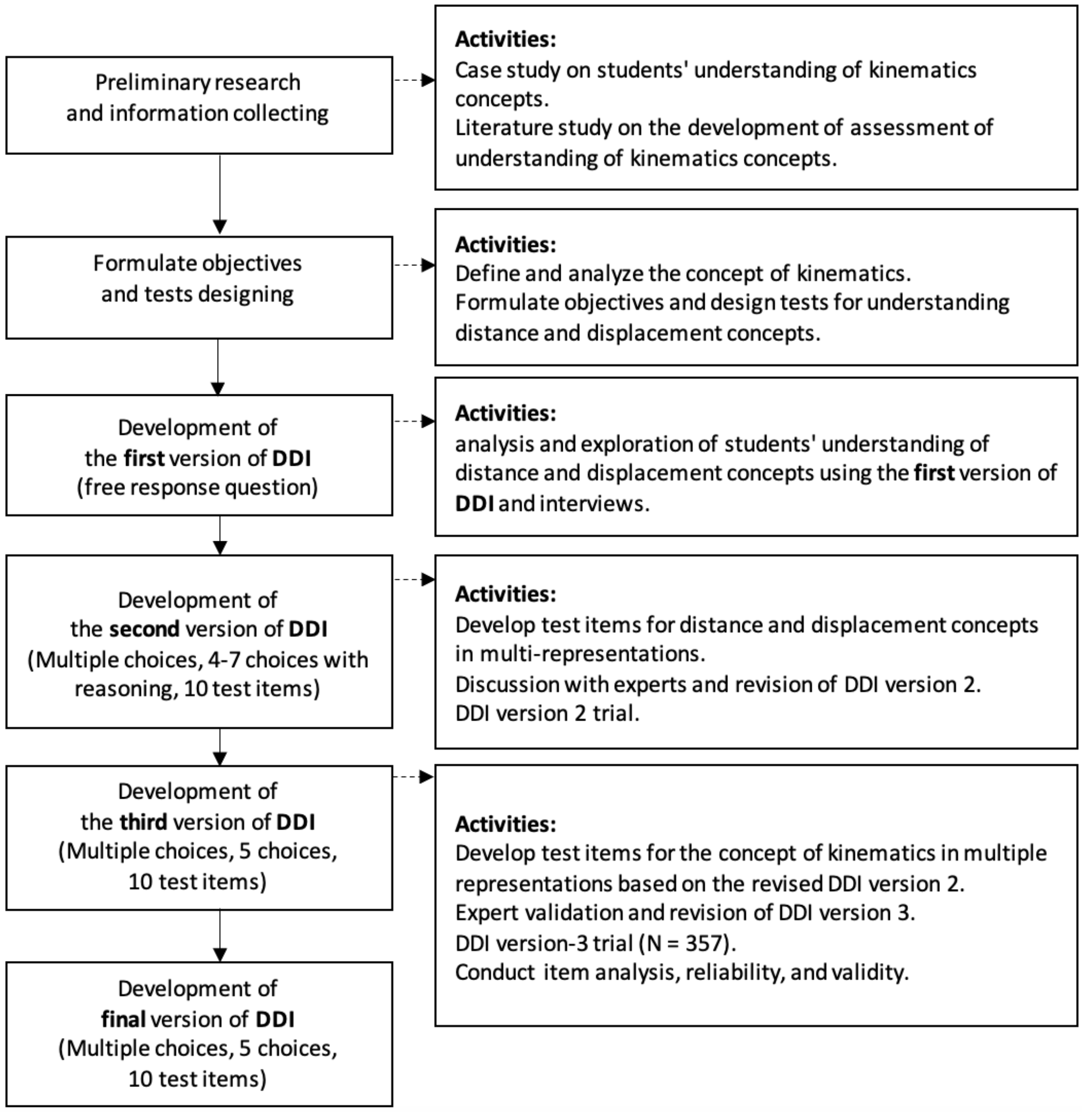


Figure 1. DDI research and development stages

Initial research and information gathering were conducted with a systematic review of articles assessing mastery of kinematics concepts. This activity has provided data and information about ideal assessments that can be constructed further. This data and information is used to formulate objectives and design test items. Based on the initial research that was carried out, DDI was developed to explore students' understanding of the concepts of distance and displacement in detail with various multiple representations. Next, formulating the objectives and designing the test items were used to develop DDI version 1.

DDI version-1 is designed as a free response question with five questions. Free-response questions were given to 21 students and continued with interviews. Interviews with students were conducted to explore students' understanding and way of thinking regarding the concepts of distance traveled and displacement in five representations: mathematics, graphics, images, tables, and verbal. Students' responses to free-response questions and short interviews with them were analyzed qualitatively. This analysis was carried out to find out how naive students think. Several answer options were formulated for each question item based on students' free responses and interviews. Apart from that, other student misconceptions from the literature have been used to construct several answer options. This process has resulted in DDI version 2.

DDI version 2 has ten test items in multiple-choice format with reasons and has five to seven distractors. The reasons for each test item are used to receive constructive and informative feedback from students. The DDI version-2 that was designed was evaluated by experts consisting of physics educators. The expert team assessed the quality of the answer options, concept coverage, the quality of the representation of each test item, and the suitability between the concept and the test items that had been prepared. DDI version 2 was tested on 129 students from five universities in Indonesia. After that, validity, reliability, item analysis, and answer options analysis were carried out. This was done to determine the level of accuracy, consistency, difficulty level, discrimination index, and biserial correlation coefficient.

Meanwhile, answer options are analyzed to select and determine answer options that will be used in developing DDI version 3. This analysis was carried out to reduce the number of options for each item to five. The five options are selected from the most effective options for each question item, and the ineffective options are eliminated. In addition, several answer options on several items were revised according to students' open options and reasons in writing. DDI version 2, revised and improved based on expert advice, data analysis results, and student feedback, produces DDI version 3.

DDI version-3 was developed in twenty test items in multiple-choice format with five options for each test item. DDI version 3 was tested on 357 students from eleven universities spread throughout Indonesia. The DDI version-3 trial data was analyzed using validity, reliability, item analysis, and exploratory factor analysis tests. In the final stage, slight revisions to several questions were carried out based on the expert team's suggestions.

Results and Discussion

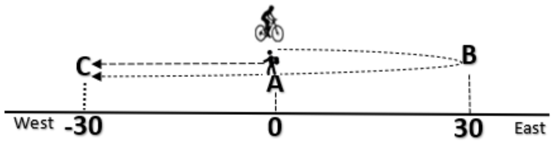
Construction of DDI

The DDI developed is based on the concept of distance and displacement, which has yet to be explored by professional assessments developed previously. Apart from that, DDI was created with multiple representations (images, tables, graphs, mathematics, and verbal) so that it can explore students' more complete and complex understanding. Other research has also stated that using multiple representations is essential for achieving competence and can reveal students' complex ideas and knowledge (Ainsworth, 2006; Mainali, 2021; Tan et al., 2022).

DDI consists of 10 test items, each revealing one concept and one representation. Several DDI questions in multi-representation are shown in Figure 2. The scope of concepts in DDI differs from those in kinematics assessments that have been previously developed professionally. The Test of Understanding Graphs in Kinematics (TUGK) was developed only in graphical representation, and the Kinematics Concept Test (KCT) was developed in graphical, image, and table representation. Meanwhile, DDI was developed in a complete representation: graphs, pictures, tables, verbal, and mathematics.

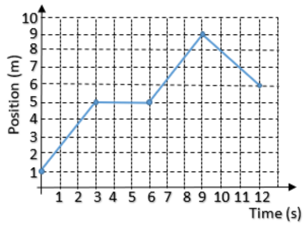
DDI was developed with multi-representations (graphics, images, numerical, verbal, and formal), which is expected to explore students' more complete and complex understanding. Some research findings reveal that many students have understood a concept in one representation but cannot understand it in another. This study revealed that many students needed help understanding the concept of distance and displacement in mathematical representation. Still, they were able to understand the concept in pictorial representation. Such understanding indicates students' partial understanding and not a comprehensive understanding of the concept. The DDI constructed in this multi-representation can thoroughly reveal the understanding of students who are still partial and the understanding of students who can understand complexly and thoroughly. Other research has also stated that using multiple representations is essential in achieving competence and can reveal students' complex ideas and understanding (Ainsworth, 2006; Mainali, 2021; Tan et al., 2022).

1. A cyclist moves at a speed of 30 m/s from point A eastward to point B, then back westward to point C. At the same time, a pedestrian moves at a speed of 10 m/s from point A straight to point C to the west. Choose the correct mileage statement!



a) The distance traveled by pedestrians is greater than that of racers.
b) Pedestrians travel less distance than racers.
c) Pedestrians travel the same distance as racers.
d) The distance traveled by pedestrians is greater than that of racers.
e) The distance traveled by pedestrians is less than that of racers.

3. Two objects are moving in a straight path. The position of the object for 12 seconds (i.e., from t=0 to t=12) is shown in the following graph.



How far does the object travel after moving for 12 seconds (from t=0 to t=12)?
a) 5 m
b) 6 m
c) 11 m
d) 13 m
e) $13+3\sqrt{2}$ m

2. The equation X(t) = 4 + 4t – t2 is the equation for the position of an object moving in a straight line, with x in meters and t in seconds. How far does the object travel during the first 3 seconds (i.e., from t=0 to t=3)?
a) 3 meters
b) 5 meters
c) 7 meters
d) 11 meters
e) 26 meters

4. The following table shows two objects moving in a straight path, their respective positions in the first five seconds.

Time (s)	0	1	2	3	4	5
Position of object 1 (m)	5	15	10	20	25	30
Position of object 2 (m)	0	5	15	20	35	40

After moving for how many seconds (since t=0) do the two objects cover the same distance?
a) After moving for 2 seconds
b) After moving for 3 seconds
c) After moving for 4 seconds
d) After moving for 5 seconds
e) The two objects never travel the same distance

5. Two basketball players stand at the center of the basketball court. The first player strolls straight toward the edge line under the basketball basket, and the second dashes straight toward the corner of the court. Which of the following statements is correct?
a) The distance traveled by both players is the same.
b) The distance traveled by the first player is greater than the second player.
c) The distance traveled by the first player is smaller than the second player.
d) The distance traveled by the first player is greater than or equal to the second player.
e) The distance traveled by the first player is less than or equal to the second player.

Figure 2. Several DDI items with different representations

The number of tests in the final version of DDI is ten items, each functioning to reveal one concept in one representation, as shown in Table 1. DDI analyzes students' conceptual understanding of distance traveled and displacement. It is essential to understand these concepts correctly because they will influence the understanding of the following concepts: speed, velocity, and acceleration. Distance and displacement, speed, velocity, and acceleration are the most fundamental concepts in physics (Clement, 1982; Jufriadi & Andinisari, 2020; Pulgar et al., 2020).

A general description of DDI construction, when compared with TUGK and KCT in detail, is shown in Table 1.

Table 1. Overview of DDI construction compared with TUGK and KCT

Kinematics concept	Representations				
	Pictures	Tables	Graphs	Mathematics	Verbals
Acceleration	Y	Y	XY	-	-
Velocity	Y	Y	XY	-	-
Displacement	**Z**	**Z**	XY **Z**	**Z**	**Z**
Distance	**Z**	**Z**	**Z**	**Z**	**Z**

X: Concepts assessed and representations used by TUGK
Y: Concepts assessed and representations used by KCT
Z: Concepts assessed and representations used by DDI

Psychometric analysis of DDI

Psychometric analysis of DDI includes a statistical discussion of validity and reliability, item analysis, and factor analysis (Hughes, 2018; Sullivan, 2011; Truijens et al., 2019). DDI validity analysis includes content, construct, and language aspects. This validity and reliability analysis was carried out to ensure that the DDI was capable and consistent in measuring mastery of the concepts of distance and displacement. DDI item analysis evaluates the item difficulty index, discriminative index, and point-biserial coefficient (Ding et al., 2006). The item difficulty index is a measure of the level of difficulty of a single test item, the item discriminatory index is a measure of the discriminating power of each item on a test, and the item point-biserial coefficient is a measure of the consistency of one test item with the entire test. The criteria widely used and suggested by Ding et al. are 0.3 – 0.9 for the difficulty index, for the discriminative index more than 0.3, and the point-biserial coefficient more than 0.2 (Ding et al., 2006). Analysis was carried out on the results of the expert team's assessment and the results of students' answers.

Five material experts and assessment experts have examined DDI version 2 and DDI version 3. They suggest improvements, especially regarding problems, question formulations, answer choices, and representations for each concept. Based on their observations, DDI has used five representations to test the basic concepts of distance traveled and displacement. Each item uses one representation to assess one concept. Apart from that, DDI version 3 has met coverage regarding concepts, construction, and language used. Each question item is correct and appropriate in assessing the concepts of distance and displacement. The concepts of distance and displacement have been represented in five representations, and the answer choices presented have fulfilled the aspects of logic and homogeneity. The DDI construction also presents questions, answer choices, pictures, tables, graphs, and mathematical equations clearly and communicatively. So, experts and educators generally state that the final version of the DDI is an adequate instrument for assessing students' knowledge of the concept of distance and movement.

The quality of the assessment and the level of trust of the expert team were analyzed by calculating the Intraclass Correlation Coefficient (ICC) and reliability values. The ICC and reliability values between expert teams are 0.749 and 0.746. The ICC value is in the range of 0.5 to 0.75, namely adequate criteria. Meanwhile, reliability between expert teams of more than 0.6 is within very good criteria. So overall, the quality of the expert team's assessment is good, and the assessment results can be trusted. Meanwhile, assessing the validity of the DDI question items is appropriate and meets the material, construction, and language aspects. The validity of the test items is assessed by calculating the Aiken coefficient, shown in Table 2. This level of validity is based on the minimum limit for the validity of the test items of 0.76 (Aiken, 1985).

Table 2. Validity of DDI based on expert assessment

Aspects	Aiken's V	Validity
Material	0,79	Valid
Construction	0,91	Valid
Language	0,89	Valid

Analysis of the DDI trial results was carried out based on student answers. The DDI trial was carried out by 357 students from eleven universities in Indonesia. Unidimensionality analysis shows that the items on the DDI can measure fundamental constructs and the same attributes. The calculated variance value explained by Rasch measure is 24.3%, similar to the expected value, namely 23.7%. So, the unidimensionality requirement of 20% can be met, and the variance that the instrument cannot explain is mostly below 10%. DDI unidimensionality analysis based on student answers is shown in Table 3.

Table 3. DDI unidimensionality analysis based on student answers

Table of STANDARDIZED RESIDUAL variance in Eigenvalue units = Item information units

		Eigenvalue	Observed		Expected
Total raw variance in observations	=	13.2143	100.0%		100.0%
Raw variance explained by measures	=	3.2143	24.3%		23.7%
Raw variance explained by persons	=	1.5626	11.8%		11.5%
Raw Variance explained by items	=	1.6518	12.5%		12.2%
Raw unexplained variance (total)	=	10.0000	75.7%	100.0%	76.3%
Unexplned variance in 1st contrast	=	2.2054	16.7%	22.1%	
Unexplned variance in 2nd contrast	=	1.5685	11.9%	15.7%	
Unexplned variance in 3rd contrast	=	1.2265	9.3%	12.3%	
Unexplned variance in 4th contrast	=	1.0331	7.8%	10.3%	
Unexplned variance in 5th contrast	=	1.0021	7.6%	10.0%	

Checking the validity of the DDI instrument and items that do not match (outliers or misfits) is carried out by calculating the Outlier Mean Square (MNSQ), Outlier Z-Standard (ZSTD), and Point Measure Correlation (Pt Mean Corr) values. The MNSQ value received is: 0.5 < MNSQ < 1.5, the ZSTD value received ranges from -2 < ZSTD < +2, and the Pt Mean Corr value received is 0.4 < Pt Measure Corr < 0.85. The average calculation result for the MNSQ outfit is 1.03, and the ZSTD outfit is -0.24. So, in general, DDI items can be categorized as fit, and the quality of the items is acceptable and functions normally. Apart from that, the reliability value of the questions is 0.88, which shows that the DDI instrument has quite good reliability (0.80 - 0.90) (Sumintono & Widhiarso, 2013). Analysis of the interaction between respondents and items is in the criteria of good results. So, the DDI instrument shows that there is conformity between the respondent and the instrument used. This analysis is based on the results of calculating the Cronbach's alpha value (KR-20) of 0.71. The results of calculating the average values for the MNSQ outfit, ZSTD outfit, and KR-20 are shown in Table 4.

Table 4. Calculation of MNSQ outfit and ZSTD outfit values

SUMMARY OF 10 MEASURED (NON-EXTREME) Item

	TOTAL SCORE	COUNT	MEASURE	MODEL S.E.	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD
MEAN	172.9	357.0	.00	.13	.99	-.27	1.03	-.24
SEM	7.5	.0	.12	.00	.07	1.27	.15	1.31
P.SD	22.6	.0	.36	.00	.20	3.80	.44	3.93
S.SD	23.8	.0	.38	.00	.21	4.00	.46	4.15
MAX.	205.0	357.0	.61	.13	1.45	8.14	2.24	9.90
MIN.	135.0	357.0	-.50	.12	.80	-3.56	.72	-3.42

REAL RMSE .13 TRUE SD .33 SEPARATION 2.54 Item RELIABILITY .87
MODEL RMSE .13 TRUE SD .33 SEPARATION 2.65 Item RELIABILITY .88
S.E. OF Item MEAN = .12

SUMMARY OF 357 MEASURED (EXTREME AND NON-EXTREME) Person

	TOTAL SCORE	COUNT	MEASURE	MODEL S.E.	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD
MEAN	4.8	10.0	-.01	.83				
SEM	.1	.0	.08	.02				
P.SD	2.6	.0	1.47	.30				
S.SD	2.6	.0	1.47	.30				
MAX.	10.0	10.0	3.54	1.86				
MIN.	.0	10.0	-3.53	.64				

REAL RMSE .90	TRUE SD 1.16	SEPARATION 1.29	Person RELIABILITY .62
MODEL RMSE .88	TRUE SD 1.17	SEPARATION 1.33	Person RELIABILITY .64
S.E. OF Person MEAN = .08			

Person RAW SCORE-TO-MEASURE CORRELATION = .99
CRONBACH ALPHA (KR-20) Person RAW SCORE "TEST" RELIABILITY = .71 SEM = 1.41

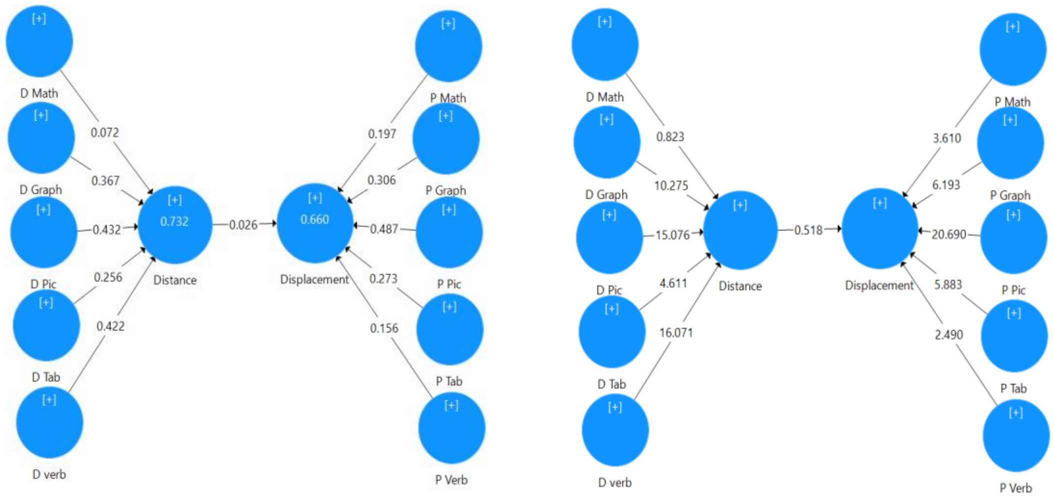
The differentiating power of questions in Winstep is done by identifying groups of respondents based on the respondent separation index. Based on Table 4, the item separation value is 2.54 for questions and 1.29 for persons. It shows that the quality of the DDI is quite good regarding question items, and overall, respondents are getting better. For more careful grouping, the strata equation (H) is used. Analysis of respondents obtained a separation value of 1.29, so the value of H = 2.05, can be interpreted that groups of people can be divided into 2 groups. The question item separation value is 2.54, so the H value = 3.72, so it can be interpreted that there are 3 groups of question items. In addition, the average logit value of 0.00 indicates that respondents have little diversity in the measured construct. It happens because the respondents come from a uniform level of education and age, even though the demographics of the students' origins are diverse.

Meanwhile, the items' difficulty level is divided into items in the easy and medium categories and items in the difficult category, shown by logit values ranging from – 0.5 to 0.61. The calculation of the logit value is shown in Table 5. Based on the evaluation of the psychometric properties, the measurements carried out show quite good and significant results. So overall, the actual data obtained is by the Rasch model requirements so that further analysis can be applied.

Table 5. Fit test of DDI items

ENTRY NUMBER	TOTAL SCORE	TOTAL COUNT	MEASURE	MODEL S.E.	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD	PTMEASUR-AL CORR.	PTMEASUR-AL EXP.	EXACT MATCH OBS%	EXACT MATCH EXP%	Item
2	135	357	.61	.13	.82	-3.10	.75	-2.88	.64	.54	82.9	74.3	JG
7	138	357	.56	.13	.80	-3.56	.72	-3.42	.66	.54	83.2	73.9	PG
3	163	357	.15	.13	.86	-2.67	.82	-2.49	.60	.53	76.0	71.3	JP
10	170	357	.04	.12	.91	-1.70	.89	-1.43	.57	.52	75.1	70.6	PV
8	172	357	.01	.12	1.11	2.11	1.12	1.53	.46	.52	66.2	70.4	PP
4	173	357	-.01	.12	.92	-1.70	.87	-1.81	.57	.52	71.9	70.4	JT
9	177	357	-.07	.12	.88	-2.56	.82	-2.52	.59	.52	74.9	70.3	PT
6	195	357	-.35	.12	.88	-2.68	.81	-2.54	.58	.50	76.0	69.8	PM
5	201	357	-.44	.12	1.45	8.14	2.24	9.90	.17	.50	60.2	69.7	JV
1	205	357	-.50	.12	1.26	5.01	1.29	3.26	.34	.49	61.4	69.9	JM
MEAN	172.9	357.0	.00	.13	.99	-.3	1.03	-.2			72.8	71.1	
P.SD	22.6	.0	.36	.00	.20	3.8	.44	3.9			7.6	1.6	

DDI structural analysis uses the Confirmatory Factor Analysis (CFA) technique. The results of the DDI factor analysis are shown in Figure 2. Several DDI items with different representations. The relationship between variables for all question items is positive. Each question item has a fairly high loading factor in measuring the latent factors so the questions prepared are very good in measuring the construct of each student's understanding of the concept of kinematics. Except for questions with mathematical representation.



a) Loading factor value b) t value

Figure 3. Factor analysis of DDI construct

Figure 3 indicates that most items in the various representations are significant because they have a loading factor value of more than 0.3. This loading factor value corresponds to the t value which shows that $t_{count} > t_{critical}$. The critical value at the 95% significance level is 1.96. From Figure 3, most of the t-calculated values for each question item are more than 1.96. Most DDI items are significant based on the loading factor and t value. However, specifically for questions with mathematical representation, the loading factor value is 0.072, and the t value is 0.823. This value indicates that the question item is not significant. However, these items are still maintained, also, students' understanding of distance traveled and displacement concepts in mathematical representation could be much higher.

Conclusion

DDI is constructed in multiple representations, namely pictures, tables, graphs, mathematics, and verbal which are used to assess students' understanding of the concepts of distance and displacement. Expert assessment of the DDI shows that the DDI is an instrument that can be used to assess adequate student understanding. In addition, analysis of the results of trials on a large scale illustrates that the DDI has met the psychometric properties of a reliable and adequate instrument. The high validity and reliability values, distribution of questions, and expert opinions indicate that the DDI is suitable for assessing students' understanding of the concepts of distance traveled and displacement. Analysis of the structure of students' knowledge of the concepts of distance and displacement shows that students' perceptions of each question item are different according to their representation. Students who can answer correctly in one representation may not necessarily be able to answer correctly in another representation.

Furthermore, students' choice of answers to each DDI question item can be used as a reference to identify common student errors. In addition, it is recommended to develop a concept understanding assessment constructed from the TUGK, KCT, and DDI instruments to assess students' understanding of kinematics concepts.

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