

Physics Learning Review: Autonomy Support, Gender Gap Reduction, and Measuring Mathematics Reasoning Ability

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Abstract

Physics and mathematics learning outcomes have specific cognitive development implications. Some empirical studies in the learning of physics have focused on gender gap reduction using interactive engagement (IE) learning environments. Interactive engagement classrooms differentiate by dialectic approach and autonomy supportive behavior; seeking to engage the intrinsic motivation within students. This bounded systematic literature review synthesizes manuscripts on (a) mathematics/physics cognitive development, (b) subject specific autonomy supportive behavior, and (c) physics learning gender gap reduction. Is reasoning ability an important mediating factor in evaluating physics learning outcomes? This systematic review has implications for researchers, supervisors, and teachers who are addressing subject specific instructional needs, or are continuing empirical research in physics learning. Supervisors of physics instructors need to have differentiated assessment instruments to negotiate responsibilities in clinical observation collaborative conferences. The purpose of this review is to bridge the pioneering work in mathematics and physics research; and inform concurrent investigations. It is recommended that future physics learning studies additionally measure mathematics reasoning ability using a concept inventory instrument designed to measure 'structure sense'.

1. Introduction

This systematic review of the literature will present current research paradigms in physics and mathematics learning. Included is an analysis of conventional research methodologies under three theoretical lenses. Current research in mathematics

learning will be linked to improved reasoning abilities common to both disciplines [6]. As a result, new research questions can be posed to frame continued physics learning investigations inclusive of *structure sense*.

Mathematics reasoning skills have been shown to be factors in decisions to enroll in physics courses. Multiple studies investigating *interactive engagement* (IE) learning environments have shown that specific autonomy supportive instructional practices reduce gender gap performance in physics achievement [3], [5], [6], [16]. One investigation finds reasoning ability among specific populations is a significant indicator to success in physics classes where interactive engagement (IE) and autonomy support are present [5]. The longitudinal effect of underdeveloped reasoning skills may contribute to decreased performance in physics learning for certain populations [9].

2. Objectives of the study

An objective of this review is to examine the extent of physics learning studies measurement of the mathematics cognitive development construct, *sense making*. Specific teaching methods are required for proper vertical and horizontal integration of science (and mathematics) subject matter content [7]. The most significant contribution of this review is its potential to be a foundation for concurrent discussions on:

1. improved pedagogical techniques addressing cognitive development in *sense making* and *thinking mathematically*,
2. gender gap reduction in the learning of physics and mathematics, and
3. autonomy supportive interventions common in IE subject specific instructional settings.

A *Euclidian Space* may be viewed as a vector space with the *usual metric* (distance) explored in secondary physics and mathematics education [14]. This focus on mathematical conceptual

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understanding, a refinement *structure sense*, herein termed *metric sense*; is hypothesized to be instrumental in building empirical knowledge in physics instruction and the assessment of learning outcomes.

3. Purpose and guiding question

The purpose of this review is to clarify the need [4], [5], [9], [13] regarding concurrent research activity significantly impacting future knowledge production in physics and mathematics learning. Additionally, this review may inform researchers seeking refinement of specific instructional design models for increased student performance outcomes [7]. A thematic focus for this review is necessary since cognitive development, interactive engagement, and gender gap reduction are each imperative considerations for improved pedagogical subject specific instruction [7], [13]. The following question guides the review. What pedagogical behavior must be considered in future investigations:

1. analyzing subject specific teacher autonomy support in a classroom experience,
2. exploring gender gap reduction in the learning of physics, and
3. measuring *mathematical thinking*.

4. Subject specific thematic focus

A framework was needed which depicts subject dependent individual learning processes. A framework was found in the “model for the analysis of student performance” [7]. The model incorporates the dimensions of classroom interaction, teacher expertise, cognitive abilities, and motivational behaviors. The model allows for a distinction between surface level and deep structure planning and instruction. This review seeks a cross-curricular view of current research in *deep learning strategies* through *sense making* cognitive development [7], [13], [19]. Schoenfeld [19] finds that without skilled instruction involving proper deep learning strategies, counterproductive conceptualizations can occur [12], [17]. Three compatible conceptual foci for the reviews’ guiding question are now presented.

4.1. Review conceptual focus: Autonomy Supportive Interventions (ASI) within Instructional Engagement (IE) settings

A framework must allow for the exploration of relationships between teacher and student, focusing on the student motivation aspect of pupil developmental and academic achievement. An

understanding of student cognitive and social development is essential to understanding student motivation. Abandoning impersonal relationships between teacher and student, which facilitate basic psychological developmental needs of the student, will negatively affect the learning experience and reduce academic success. *Self-Determination Theory* was chosen with a conceptual framework based on stages of human development [18]. Ryan and Deci [18] have identified a *taxonomy of human behavior* utilizing a continuum of motivation from impersonal through internal. Dimensions of the human motivation conceptual model consist of *amotivation*, *extrinsic motivation*, and *intrinsic motivation*. Intrinsic motivation increases academic success, while meeting a student’s basic psychological needs.

It is conducive to this review to utilize an autonomy supportive conceptual framework, useful within classroom environments, which increase conceptual understanding of specific subject matter toward better academic performance [18]. The *dialectic* approach within self-determination theory suits this purpose and is an inclusionary criterion for the review. Conceptual understanding building in physics and mathematics entails a combination of; (a) specialized content specific instruction [4], [7], (b) student voluntary exposure to challenging tasks, and (c) *deep* involvement in subject matter [21].

4.2. Review conceptual focus: Gender gap reduction in physics learning outcomes

The Global Gender Gap Index provides an appropriate lens for depicting instructional elements pursuant of gender gap reduction in physics learning. The index measures the four key areas of health, education, economics and politics [8]. These areas are consistent with the dimensions of the chosen thematic model investigating science specific learning performance. Of particular importance to this review’s inclusionary criteria are the conceptual impedances to the disparity in the subindex “educational attainment” [8]. Having a lens appropriate for including articles on gender gap reduction, attention is now turned to a conceptual framework for selecting manuscripts specific to *thinking mathematically*.

4.3. Review conceptual focus: Cognitive development in sense making and thinking mathematically

A COACTIV study provides a conceptual framework operationally defining mathematics

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teacher competence and effective instruction [4]. Two dimensions of this conceptual framework are specific to cognitive development and compatible to the thematic focus of the review [4], [7]. The *facet of knowledge* constructs of the pedagogical knowledge domain, specifically “knowledge about representing and explaining mathematics”, captures the hidden mediating variable exemplified by this review [4]. The construct knowledge of students’ *mathematical thinking* is also representative of explored mediating variables. The *motivational orientations* operational definition of subject specific behavioral tendencies, additionally supports selecting the framework pursuant the review’s guiding question [4]. Having described compatible conceptual foci (lenses) supporting an overarching thematic focus, attention is now turned to the remaining aspects of this systematic review inquiry.

5. Review method sources

Manuscript selection was drawn for their ability to synthesis empirical findings according to the aforementioned theoretical and conceptual frameworks. Although Boolean searches were performed for each conceptual focus, further refinement on the article selection process was determined by construct inclusions of the remaining conceptual foci. The unique nature of this review posed difficulty formulating criteria for inclusion of

articles reporting on pioneering research in their respective fields. To assist the researcher, the author utilized a criteria rubric specified in Figure 1. The rubric served in scoring article relevance to the review’s guiding question. Additionally, the rubric scoring (see Table 4.) allowed for broad descriptive interpretations of the state of current research in cross-disciplinary subject research.

5.1. Sources for the review: Selection, data extraction, and coding for gender gap reduction

A significant portion of the articles studying gender gap reduction in physics learning outcomes utilize a concept inventory instrument in an *Interactive Engagement (IE)* instructional setting. A limited quantity of research articles empirically testing physics outcomes required the author to carefully select articles pursuant to the thematic focus, yet also including aspects of motivation and cognitive skills analysis.

The gender gap research articles selected have findings from gender gap closure to significance in data revealing reverse gender gap conclusions (see Table 1.). Articles with significant gender gap findings based on normalized gains in physics learning outcomes; prompted their inclusion in the review.

Table 1. Characteristics of research papers in physics achievement and/or physics gender gap reduction

Author(s)	Year	Locus	Journal	Conceptual Focus	Method of Analysis	Concept Inventory	IE Design	Gender Gap/ Normalize Gain
Coletta and Phillips [5]	2005	United States	<i>AJP</i>	Reasoning Cognitive Develop	Correlation	FCI, Lawson	Yes	Reasoning Mediating Variable
Lorenzo, Crouch, and Mazur [16]	2006	United States	<i>AJP</i>	Gender Disparity	t-test	FCI	Yes	Gap Closure
Kost, Pollock, and Finkelstein [13]	2009	United States	<i>PRST</i>	Gender Disparity	Regression Modeling	FMCE	Yes	Gender Gap Mediating Variable
Coletta, Phillips, and Steinert	2012	United States	<i>AIP</i>	Reasoning Cognitive Develop / Gender	t-test	FCI, Lawson	Yes	Mediating Variable / Reverse Gap

[6]				Disparity				
Adegoke [3]	2012	Nigeria	PE	Gender Disparity	Quantitative ANCOVA	QPIG, QPAT	Yes	Gap Closure
Hazari et al. [9]	2013	United States	JCST	Physics Identity	Factor Analysis	PRiSE project survey	No	Mediating Variable
Shi, He, Wang, and Huan [20]	2015	China	EJMST E	Gender Disparity	t-test	USTL	No	Gap Closure

Note. PE = Physics Education; AJP = American Journal of Physics; PRST = Physical Review Special Topics-Physics Education Research; JRST = Journal of Research in Science Teaching; AIP = American Institute of Physics; EJMSTE = Eurasia Journal of Mathematics, Science & Technology Education; FCI = Force Concept Inventory; FMCE = Force and Motion Concept Evaluation; Lawson = Lawson Classroom Test of Scientific Reasoning; PRiSE = Persistence Research in Science and Engineering; USTL = University of Science and Technology Liaoning Laboratory Quiz; QPIG = Quantum Physics Instructional Guide; QPAT = Quantum Physics Achievement Test

The seven gender gap studies identified were coded to nodes conventionally characteristic of *Newtonian* physics content. The Force Concept Inventory (FCI) instrument was found beneficial to the field studying physics outcomes [5], [6], [16]. Data was also extracted and coded to emergent nodes descriptive of methodological choices in investigating physics learning performance.

Instructional behavior found in gender gap studies focus on methods of instruction within interactive engagement (IE) settings (see Table 4.) [3], [5], [6], [13], [16]. Data was extracted from gender studies and coded to nodes descriptive of motivational controls. Where motivational controls were found in gender studies, data was coded according to constructs of the *dialectic* conceptual framework [11], [19].

5.2. Sources for the review: Selection, data extraction, and coding for intrinsic motivation

Articles searched and selected along the focus of *autonomy-supportive instruction* (ASI), indirectly support, but conventionally do not directly specify (IE) instructional settings utilized in physics concept inventory experiments [2], [21]. There are limited quantities of research articles with a high focus on motivation and concurrently testing physics and mathematics performance under the aforementioned thematic focus (see Table 4.). This restraint required this review to rigorously select articles pursuant the thematic focus, yet also include aspects of cognitive skills analysis. The conceptual focus of the articles prompted their inclusion in the review because they are directly relevant to the subject matter content specific [4], [7] thematic framework and Autonomy Supportive Interventions (ASI) conceptual focus (see Table 2.).

Table 2. Characteristics of research papers on autonomy supportive interventions within IE

Author(s)	Year	Locus	Journal	Conceptual Focus	Method of Analysis	Motivation/Autonomy Instrument	IE design
Kaplan and Assor [11]	2012	Israel	SPE	I-Thou / SDT / ASID	Correlation / ANCOVA	ASDQ	ASIT Dialogue
Thomas and Müller [21]	2014	Austria	ZB	SDT / SEFT	t-test MANOVA	SRQ-A	Classroom / Lab
Abraham and Barker [2]	2014	Australia	AJEDP	SEMP	SEM	PMQ Constructs	N/A

Note. AJEDP = Australian Journal of Educational & Developmental Psychology; SPE - Social Psychology of Education; ZB = Zeitschrift für Bildungsforschung; SEMP = Sustained Enrolment Model for Physics; PMQ = Physics Motivation Questionnaire; ASID = Autonomy-supporting I-Thou Dialogue; SDT = Self-Determination

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Theory; ASIT = Autonomy-Supportive I–Thou Dialogue Program; SRQ-A = Academic Self-Regulation Question; ASDQ = Autonomy Supporting Dialogue Questionnaire; SEFT = Stage-environment Fit Theory

Extracted data was coded to prefigured and emergent nodes descriptive of autonomy supportive behaviors. Nodes were also created to code instructional behaviors specific to physics gender gap reduction and developing cognitive function. Included nodes were, applying physics to a broader world view [21], writing exercise mitigation [6], among other emergent autonomy supportive activity. Data was extracted from the studies on motivation and coded to nodes descriptive of gender gap reeducation and mathematics cognitive development. Where constructs of cognitive development were found in ASI manuscripts, data was coded across respective conceptual frameworks.

5.3. Sources for the review: Selection, data extraction, and coding for cognitive reasoning ability increases in thinking mathematically and applying structure sense

Articles investigating increased cognitive math function center on operational definitions including *sense making*, *symbol sense*, and *structure sense* (functions operational on, and expressions symbolized on the set \mathbf{R} [15], [17]), [1], [10], [22] (see Table 3.). Some articles included construct considerations of motivation, cognitive development, and instructional design. Of particular significance are studies pursuant of increased physics competency through *sense making* in mathematical expressions [4], [6]. Additional criteria for manuscript inclusion were studies germane to the thematic focus centering on operational definitions consistent with *deep structures* [4], [7]. The conceptual focus of the articles and cognitive reasoning operational definition of *sense making* prompted their inclusion in the review.

Table 3. Characteristics of research papers on *Sense Making* and *Thinking Mathematically*

Author(s)	Year	Locus	Journal	Conceptual Focus	Method of Analysis	Mathematical Sense Making
Schoenfeld [19]	1988	USA	<i>EP</i>	Cognitive Development	Qualitative Bounded Case	Sense Making
Arcavi [1]	1994	Canada	<i>LM</i>	Cognitive Development	Qualitative Grounded Theory	Symbol Sense
Linchevski and Livneh [15]	1999	Canada Israel	<i>ESM</i>	Cognitive Development	Mixed Descriptive Statistics	Structure Sense
Hoch and Dreyfus [10]	2004	Israel	<i>PME</i>	Cognitive Development	Mixed Descriptive Statistics	Structure Sense
Novotna and Hoch [17]	2008	Czech Republic Israel	<i>MERJ</i>	Cognitive Development	Theoretical Hypotheses Testing	Structure Sense
Baumert, <i>et al.</i> [4]	2010	United States / Europe	<i>AERJ</i>	Cognitive Development	SEM	Sense Making
Van Stiphout, Drijvers, and Gravemeijer [22]	2013	Netherlands	<i>IEJME</i>	Cognitive Development	Correlation	Symbol Sense Structure Sense

Note. *LM* = For the Learning of Mathematics; *PME* = Proceedings of the 28th Conference of the International Group for the Psychology of Mathematics Education; *ESM* = Educational Studies in Mathematics; *MERJ* = Mathematics Education Research Journal; *EP* = Educational Psychologist; *IEJME* = International Electronic Journal of Mathematics Education; *AERJ* = American Educational Research Journal

Data extraction and coding centered on pedagogical techniques addressing cognitive development in *sense making* and *thinking mathematically*. The seven research articles identified were coded to nodes conventionally characteristic of mathematical vector spaces [14]. Vector spaces are natural generalizations of a Euclidian Space (*Newtonian* physics course content space). Nodes were prefigured to mathematical conceptual descriptors; (a) mathematical functions, (b) the real number set **R**, and (c) and a metric (usual distance on **R**). Emergent nodes were coded to the sense making operational definitions: *symbol sense*, *structure sense*, and *thinking mathematically*.

Additionally, data was extracted from mathematics cognition studies and coded to nodes descriptive of motivational controls and constructs pertinent to increased physics leaning outcomes.

Where motivational controls were found in mathematics cognition studies, data was coded according to constructs of the dialectic conceptual framework [11], [18].

6. Data evaluation and analysis

Data analysis for this review sought to synthesize current literature in cross-disciplinary subject research. A thematic focus was provided encompassing the goal. A rubric assisted the researcher in evaluating selected articles according to the review's thematic focus. Three levels of each conceptual focus are formulated according to conventional elements of research design, and assigned to manuscripts (see Figure 1. and Table 4.).

Criteria/Level	Conceptual Focus Level		
	High – 2	Medium – 1	Low - 0
Concept Inventory (CI) Instrument	CI instrument is an element of research purpose; the conceptual framework; the methodology procedure, data analysis, and findings; and limitations or implications of research paper	CI instrument is an element of research purpose; the framework; OR the methodology procedure, data analysis, and findings OR the limitations of research paper	CI instrument is an element of ONLY the limitations or implications of research paper OR not considered at all
IE design	IE design is an element of research purpose; the conceptual framework; the methodology procedure, data analysis, and findings; and limitations or implications of research paper	IE design is an element of research purpose; the framework; OR the methodology procedure, data analysis, and findings OR the limitations of research paper	IE design is an element of ONLY the limitations or implications of research paper OR not considered at all
Motivation/ Autonomy Support	Motivation /Autonomy Support is an element of research purpose; the conceptual framework; the methodology procedure, data analysis, and findings; and limitations or implications of research paper	Motivation /Autonomy Support is an element of research purpose; the framework OR the methodology procedure, data analysis, and findings OR the limitations of research paper	Motivation/Autonomy Support is an element of ONLY the limitations or implications of research paper OR not considered at all
<i>Thinking Mathematically/ Reasoning/ Sense Making</i> Focus	Thinking Mathematically / Reasoning/ Sense Making is an element of research purpose; the conceptual framework; the methodology procedure, data analysis, and findings; and limitations or implications of research paper	Thinking Mathematically / Reasoning/ Sense Making is an element of research purpose; the framework; OR the methodology procedure, data analysis, and findings OR the limitations of research paper	Thinking Mathematically / Reasoning/ Sense Making is an element of ONLY the limitations or implications of research paper OR not considered at all

Figure 1. Rubric for article relevance to the review's thematic framework

The conceptual focus level rubric assisted the author of the review in getting a broad perspective of contributions of articles utilized in the review. Each article was scored with a summative value from zero

to eight, with the higher value reflecting greater contribution to the thematic focus of the systematic review (see Table 4.).

Table 4. Article score according to the review's thematic focus and respective conceptual foci

Author(s)	Year	Criterion of Thematic Focus				Score
		Gender Gap Reeducation Focus		Cognitive Development Focus		
		Instrument	Instructional Setting Focus	IE design	Thinking Mathematically/ Reasoning/ Sense Making	
Schoenfeld [19]	1988	0	0	0	2	2
Arcavi [1]	1994	0	0	0	2	2
Linchevski and Livneh [15]	1999	0	0	0	2	2
Hoch and Dreyfus [10]	2004	0	0	0	2	2
Coletta and Phillips [5]	2005	2	1	2	2	7
Lorenzo, Crouch, and Mazur [16]	2006	2	1	2	1	6
Novotna and Hoch [17]	2008	0	0	0	2	2
Kost, Pollock, and Finkelstein [13]	2009	2	0	2	2	6
Baumert, <i>et al.</i> [4]	2010	2	2	1	2	7
Hazari <i>et al.</i> [9]	2013	2	2	0	2	6
Adegoke [3]	2012	2	1	2	0	5
Coletta, Phillips, and Steinert [6]	2012	2	0	2	2	6
Kaplan and Assor [11]	2012	0	2	2	1	5
Van Stiphout, Drijvers, and Gravemeijer [22]	2013	2	0	2	2	6
Abraham and Barker [2]	2014	1	2	1	0	4
Thomas and Müller [21]	2014	1	2	1	0	4
Shi, He, Wang, and Huan [20]	2015	1	1	0	0	2

7. Article synthesis and analysis

Before discussing specific findings, limitations, and implications of the review, it is beneficial to justify this timely review in light of

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the rubric evaluations. As stated earlier, this review is to inform research specific to physics and mathematics learning. The pioneering investigations utilized in this review have made it possible. The author commends the authors of these studies for their significant contribution toward empirical knowledge building in physics and mathematics learning. Although the rubric evaluation finds that only seven of seventeen rigorously selected articles scored above five in supporting the thematic focus; the scoring proportions help exemplify the significance of this review. Of the eleven articles scoring high in reasoning ability cognitive development investigation design; only two included significant gender gap considerations for autonomy support, concept inventory measurement, and IE design utilization [4], [5]. Of the eight articles scoring high on utilizing concept inventory instrumentation, six manuscripts included mathematics conceptualization considerations. Of the six scoring high in the evaluation of both physics and mathematics conceptualizations; four scored low or excluded autonomy support behavior analysis. This review supports a need for future investigations to simultaneously investigate relationships among all three conceptual foci stated at the onset of this investigation. The survey of research methodologies displayed in tables of this review is informative of the nature of physics and mathematics learning research. Analysis of nodes coded from the manuscripts support a continued use of the thematic focus used in this review, and may be a consideration for future investigations [4], [5], [6], [9].

8. Discussion of findings, limitations, and implications

This timely review is the first of its kind with an objective to examine the extent of physics learning studies with concurrent considerations of intrinsic motivation, mathematics cognitive development, and gender gap performance reduction. Carefully selected articles best fitting the reviews framework do not individually incorporate fully cross-curricular learning considerations. Even under this limitation, the review does have specific recommendations.

Specific teaching methods are required for proper vertical and horizontal integration of science and mathematics subject matter content [7]. Instruction void of subject specific instructional methods focus on *surface structure* processing rather than *deep learning* cognition development [7], [19]. Subject specific instructional design

dominantly implementing procedural learning can result in a lack of conceptual structure development and an inability to use mathematics and science in a meaningful way [17]. Well planned, direct teacher intervention is necessary for subject specific cognitive development [4], [15].

9. Conclusions

This review exemplifies the need for further studies in physics learning to be inclusive of considerations for reasoning ability; specifically skills in representing and explaining *structure sense* within the mathematical construct of a *Euclidian Space* [14], [15], [17]. Inclusion of *structure sense* in behaviorist studies is consistent with *second generation instructional design*, approaching a moderation of constructivism [7], [12]. As a result of the guiding question, it is found that measuring the mathematics learning construct of *metric sense* may be significant in researching physics instruction and assessment of learning outcomes [22].

This systematic review of selected literature illustrates a need for research concurrently investigating (a) autonomy-supportive behaviors specific to physics (b) instructional behaviors toward increased mathematics reasoning skills (e.g. *thinking mathematically, sense making, structure sense, metric sense*), and (c) subject specific pedagogical behaviors consistent with *second generation instructional design*. Conceptual models including content specific instructional design for increased learner performance in physics or mathematics may need to be refined to include constructs for capturing *structure sense*.

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- Lear, Jeffrey. (2016). Physics Learning Review: Autonomy Support, Gender Gap Reduction, and Measuring Mathematics Reasoning Ability. Proceedings of the Canada International Conference on Education: CICE-2016. Infonomics Society, Mississauga, ON, Canada. pp. 272-280. DOI: 10.2053/CICE.2016.0067
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