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# A Systematic Review on Robot-Assisted Special Education from the Activity Theory Perspective

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**ABSTRACT:** The design, implementation, and outcome of educational robots in special education have not been sufficiently examined in a systematic way. In particular, learner-based and contextual factors, as well as the essential roles played by various stakeholders have not been addressed when robots are used as a learning tool in special education. Therefore, a systematic review using Activity Theory was conducted to analyze 30 studies in robot-assisted special education. Content analysis of the studies reported relevant information with respect to each activity component — (a) *subject* (learners with disabilities), (b) *technology* (robots supported by instructional design), (c) *object* (target skills or behaviors), (d) *rules* (implementation procedure and performance measures), (e) *community* (learners with disabilities, special education professionals, and parents), (f) *division of labor* (among learners, professionals and parents), and (g) *outcome* (performance of target skills or behaviors). Furthermore, the study identified existing gaps from the robot-assisted special education studies (e.g., lack of parental engagement), challenges (e.g., difficulty with standardizing performance measures due to heterogeneity of learner profiles), and contradictions (e.g., opposing views among experts on the role of robots in social interactions). Finally, recommendations were made under each activity component. The study concluded that both general and domain-specific guidelines should be created for each disability category proposed in this review to assist practitioners who wish to use robots to assist special education.

**Keywords:** Educational robots, Special education, Disability, Activity Theory, Human-robot interaction, Assistive technology

## 1. Introduction

In line with the re-authorization of the Individuals with Disabilities Education Act (108th Congress, 2004), special education professionals face the urgency to identify and implement effective practices to ensure the benefits of learners with disabilities (Moeller et al., 2015). The Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan (n.d.) defines special education as education that aims to take into consideration the individual needs of learners with disabilities in order to develop both their social participation and independence. In recent decades, special education practitioners are making use of assistive technologies, which are services and technology devices that facilitate the learning process among individuals with disabilities (Ashton, 2005). Robots, as an example of assistive technologies, can effectively help learners with disabilities fulfill the requirements of subject learning (e.g., science, art) and play activities when supported by appropriate strategies (Encarnaçao et al., 2016). Although many studies have applied educational robots in special education settings, a systematic analysis on the related design, implementation, and outcome using robots in special education interventions has not been conducted, nor have applicable guidelines for robot-assisted special education been established. This review therefore aims to fill this gap.

Among various types of educational technology, robots are considered a safe and accessible learning tool to support children's flexible and programmable manipulation of real objects (Encarnação et al., 2016). The fun and engaging learning experience also lead to better learning achievements (e.g., Datteri et al., 2013). In particular, the rule-based, programmed robot-human interactions effectively keep learners with Autism Spectrum Disorder (ASD) engaged in learning. Moreover, for learners with disabilities, robots can increase their readiness to learn in the classroom through predictable and consistent human-robot interactions, which makes robots an important transition tool for helping ASD learners to progress from human-robot to human-human interactions (Alcorn et al., 2019). As current literature only provides a partial picture about the integration of robots in education, a comprehensive investigation on how to deploy robots with effective design and strategies to enhance learning in special education settings is needed. Consequently, the scope of this review includes how various types of robots have been used in combination with instructional design strategies and implementation processes in robot-assisted special education.

To understand and optimize the process of robot-assisted special education, a systematic examination of its key components is needed. This review study first applies the Activity Theory (Engeström, 2001) to analyze the contribution and agency of the stakeholders involved in the practice of robot-assisted special education, and then proposes recommendations on how to best integrate educational robots as a learning technology (Cheng, Sun, & Chen, 2018) for learners with disabilities. The Activity Theory describes the interconnectedness among social and individual processes in an activity supported by a mediating tool. Six main components of the theory include *subject*, *object*, *tool*, *rules*, *community*, and *division of labor* (Engeström, 2001). Since complex and interacting factors affect the design and perceptions of tools in special education (Pearson, 2009), it is crucial to move beyond the technology itself (robots in this case) and understand how different stakeholders can best collaborate (e.g., identifying the disability profiles, standard practices, and distributed duties) to achieve a goal. As such, an analysis based on the Activity Theory, which has been applied in numerous domain areas, will help to increase the effectiveness of using robots in special education settings.

Activity Theory has been adopted to examine the use of several types of technology in both general and special education settings (Daniels & Cole, 2002; Edwards et al., 2002; Pearson & Ralph, 2007). However, the theory has not been used to analyze the design and implementation of robot-assisted special education. In a systematic review on robotics education, Jung and Won (2018) suggested that robotics education research should shift its focus from the effects of robotic technology to learners by examining the pedagogies, teaching methods, and specific ways learners undergo meaningful learning processes. As reviews on learner-centered design and the implementation of robotic assistive technology in special education remain scant (e.g., Van den Heuvel et al., 2016), this study probes into how various components work in a special education activity system that employs robots by asking two research questions:

RQ1: What relevant features concerning the design, implementation, and outcome of robot-assisted special education can be identified through the lens of Activity Theory?
RQ2: What recommendations can be made to improve robot-assisted special education research?

## 2. Method

This systematic review aimed to analyze existing practices in designing, implementing, and measuring outcome in robot-assisted special education. The researchers identified the need for a review with specific research questions, selected the studies for review, assessed their quality, and presented the data extraction method with interpretations and recommendations for further research (Benitti, 2012; Kitchenham, 2004).

### 2.1. Search strategy and inclusion/exclusion process

Systematic searches included nine entries with keywords such as “educational robots” AND “learners with disabilities” on eight electronic databases. Figure 1 provides the flow chart of the entire selection process. The initial number of studies after the keyword searches was 784 after removal of duplicates. Then, two of the researchers conducted title, abstract, and full-text screening using ten inclusion/exclusion criteria with good inter-coding reliability ($\kappa = 0.83$). Consensus was reached via discussion for any discrepancy in the selection results. This led to a final data set of 30 studies, included twenty-seven journal papers (6 SSCI journals), two conference papers, and one book chapter.

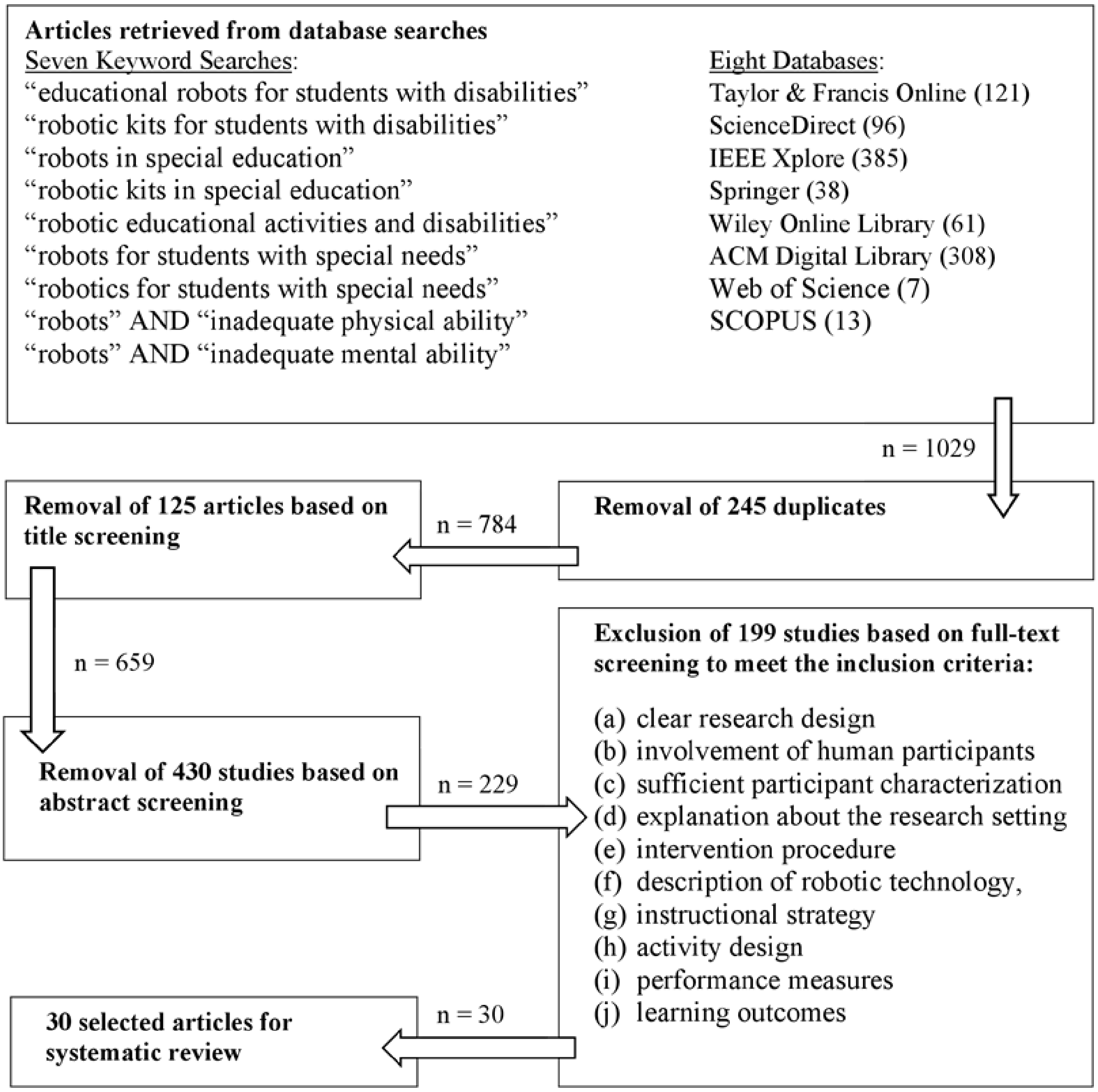

*Figure 1*. Flow chart for the article search and selection process

### 2.2. Research rigor and design of the selected studies

The researchers assessed the research rigor using *Horner's Criteria,* a widely adopted rubric for case design in special education (Moeller et al., 2015). This set of criteria was valid because case design is commonly used in special education research, and a large proportion of the selected studies employed case design. To ensure the credibility of Horner's quality indicators, the researchers checked them against the essential quality indicators for experimental research in special education (Gersten et al., 2005) and found that Horner's Criteria sufficiently fulfilled items for Describing Participants, Implementation of the Intervention and Description of Comparison Conditions, and Outcome Measures. Horner's criteria further assessed Social Validity of case design (Moeller et al., 2015). In comparison to ideal indicators for measuring qualitative methodological rigor in general education research, Horner's criteria adequately ensured Responsiveness to Social Context, Appropriateness of Sampling, Adequacy of Sampling, and Transparency of Data Collection (Fossey et al., 2002). As shown in Table 1, low percentages were reported for establishing baseline conditions (33.3%) and ensuring experimental control (46.7%), implying challenges faced by special education practitioners when designing and implementing robotic interventions. In terms of the research design, single-group interventions (e.g., summer camps) measured by pre- and post-tests (*n* = 14) and case studies (*n* = 9) were adopted most frequently (See Table S1 in Supplementary Materials).

*Table 1.* Rigor assessment of the robot-assisted special education studies

| Quality indicators | Number of studies meeting the criteria | % of studies meeting the criteria |
|---|---|---|
| 1. Participants & Settings | | |
| Participant description | 30 | 100% |
| Participant selection/recruitment | 26 | 86.7% |
| Setting description | 30 | 100% |
| 2. Dependent Variable (Outcome) | | |
| Operationally defined | 30 | 100% |
| Measurement of performance is valid and described sufficiently | 29 | 96.7% |
| Inter-observer agreement or strict confirmability checks | 15 | 50% |
| 3. Independent Variable (Treatment) | | |
| Operationally defined | 29 | 96.7% |
| Systematically manipulated by experimenter | 30 | 100% |
| Implementation fidelity established | 30 | 100% |
| 4. Baseline | | |
| Baseline conditions are operationally defined | 10 | 33.3% |
| 5. Internal Validity | | |
| Controlled for common threats to internal validity | 15 | 50% |
| Demonstrated experimental control | 14 | 46.7% |
| 6. External Validity | | |
| Experimental effects are replicated across participants, settings, or materials | 23 | 76.7% |
| 7. Social Validity | | |
| Dependent variable is socially important | 29 | 96.7% |
| Magnitude of change is socially important | 29 | 96.7% |
| Implementation is practical and effective | 29 | 96.7% |

### 2.3. Using Activity Theory to analyze robot-assisted special education studies

This review adopted Activity Theory to perform content analysis on the interplay of various components and actors in robot-assisted special education research. Since activity was defined as a system of purposeful behaviors leading to recognizable changes in human practices (Kim, 2010), the researchers examined how robot-assisted learning could lead to evolving behaviors and practices among the stakeholders. As shown in Figure 2, the framework addressed how robot products were adapted for learning, how the robotic mediation led to learning outcomes, how special education professionals created and perceived the learning environment enriched by robotic activities, and how parents were involvement in the robot-assisted interventions.

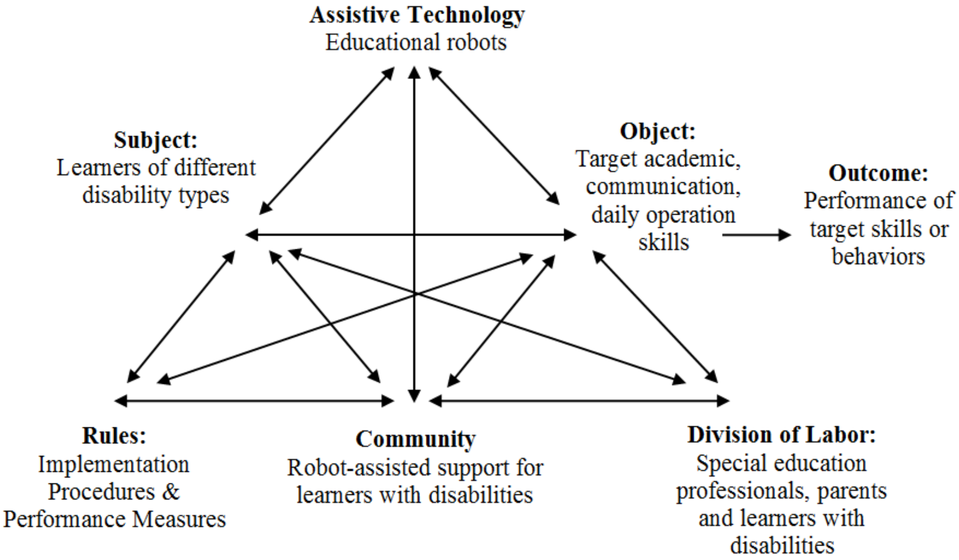

*Figure 2.* Using Activity Theory to analyze robot-assisted special education studies

*Subject* referred to learners with one or more different disabilities who participate in robot-assisted special education research; *Technology* referred to educational robots, the accompanying tools (e.g., haptic and sound generation devices) and instructional design strategies that mediated the learning. *Object* included skills and behaviors that the robotic technology aimed to improve among learners (e.g., academic, communicative, social/interactional, movement, daily operation, executive functions and perceptions, active task engagement). *Rules* included accepted practices in implementing robot-assisted interventions, for example, steps in the intervention procedures and performance measures for evaluating learning outcomes; and *Community* referred to people involved in robot-assisted interventions (e.g., learners, family, friends, professionals) and special education settings (e.g., schools, clinics) that supported the interventions. *Division of Labor* referred to distribution of duties among learners, special education professionals, and parents for undertaking robot-assisted learning interventions. *Outcome* was learners' performance in target skills as evaluated by performance measures. Two of the researchers iteratively analyzed the content from Tables S1 and S2 and identified instances based on this coding scheme.

### 2.4. Categorization of learner disabilities

During the content analysis, two of the researchers first summarized the participant profile, disability categories, learning domain and objectives, robot type, accompanying tools, research design, instruments, learning activity, role of robot, instructional strategy, performance measures, and outcomes (See Supplementary Materials for Tables S1, S2, and S3). The disabilities in each study were then grouped into six categories based on disability dimensions and types listed by the International Classification of Functioning and Disability, and Health (Perenboom & Chorus, 2003) and the Individuals with Disabilities Education Act (Office of Special Education and Rehabilitation Services, 2020). The criteria for the categorization included disability dimensions (e.g., mobility, social integration) and disability types (e.g., Intellectual Disability, Hearing Impairment) that repeatedly surfaced in the coding. When there was a discrepancy, the two coders discussed based on the established criteria and reached consensus on the final coding results.

The first category included Emotional or Attention-Related Disabilities (e.g., ASD, ADHD) involving diagnosed problems with neurodevelopment, behaviors, and communication. The second was Intellectual Disability, which referred to a general learning disorder that affected their intellectual and adaptive functioning. The third was Physical Disabilities that affected movement and physical development, and the fourth was Sensory Impairments of eyesight or hearing. The fifth was Speech Impairments, which affected one's ability to communicate, and the sixth was Unspecified Disabilities that caused learning difficulties. The coders also grouped performance measures among the studies into categories. Table S2 in Supplementary Materials shows the seven performance measure categories ranked by frequency based on the coding scheme in Table 2. It should be noted that several studies used more than one type of performance measure. Finally, the role of robot and the learning objectives were analyzed based on information provided in Tables S1 and S2 in Supplementary Materials.

*Table 2.* Coding Scheme for Performance Measures

| Code | Description |
|---|---|
| Academic Performance | • Learning outcomes in academic subjects (e.g., STEM, art) |
| Communication | • Expressive and receptive use of language (e.g., oral and listening skills)<br>• Ability to use augmentative and alternative communication technology |
| Active Task Engagement | • Taking initiatives to participate and staying focused during task<br>• Awareness, attention, curiosity, persistence throughout task |
| Social/Interactive Skills | • Ability to carry out activities with others (e.g., robot, peers, or adults) |
| Executive/Perceptual Functions | • Executive functions (e.g., working memory)<br>• Visual, auditory, haptic, spatial skills |
| Kinesthetic Behaviors | • Physical movements and motor skills<br>• Daily operations and functions |
| Interest/Motivation/Attitude | • Interest in using assistive technology for robotic programming<br>• Desire to participate in learning activities<br>• Willingness to complete learning activities |

## 3. Results and discussion

To address the first research question, findings based on the 30 studies showed the design features of learning activities for different disability categories supported by different hardware and instructional strategies, research implementation processes enacted by various stakeholders, and outcome evaluation in robot-assisted special education. To address the second research question, recommendations on how to improve robot-assisted special education were provided based on the identified gaps, challenges, or contradictions under each activity component.

### 3.1. Subject

The subjects were learners between 2 and 21 years of age with one or more disabilities. Figure 3 shows that fourteen studies focused on learners with Emotional or Attention-Related Disabilities. These learners mostly suffered from ASD and needed support on social interaction and communication (e.g., Albo-Canals, 2018). Ten studies focused on Intellectual Disability, particularly those with moderate or mild intelligent quotients, and inadequate general thinking abilities (e.g., cause-effect conceptualization) and poor sense of direction (Bargagna et al., 2018; Lee & Hyun, 2015; Park & Kwon, 2016; Pennington et al., 2014). Nine studies involved learners with Physical Disabilities. Four and three studies concerned learners with Sensory Impairments and Speech Impairments respectively. Learners with Sensory Impairments had little experience with programming (e.g., Howard et al., 2012), while learners with Speech Impairments had below-average expressive and receptive language levels (Encarnação et al., 2017; Lee & Hyun, 2015). Finally, two studies involved learners with Unspecified Disabilities displayed deficiency in reading, writing, and self-directed functions (Karna-Lin et al., 2006; Pihlainen et al., 2017).

In each study, learners received specific support and training according to the disability categories reported in Figure 3. For instance, learners with Physical Disabilities received support on overcoming severe physical limitations in order to engage in robotic play (Adam & Cook, 2013; Cook et al., 2005; Van den Heuvel et al., 2017a; Van den Heuvel et al., 2017b; Van den Heuvel et al., 2020). The main challenge for the Subject component was heterogeneity in the learners' disability profiles. Due to this great variety in disability types, each study designed its own robot-assisted learning activities and assessment methods to meet the learners' specific conditions and needs.

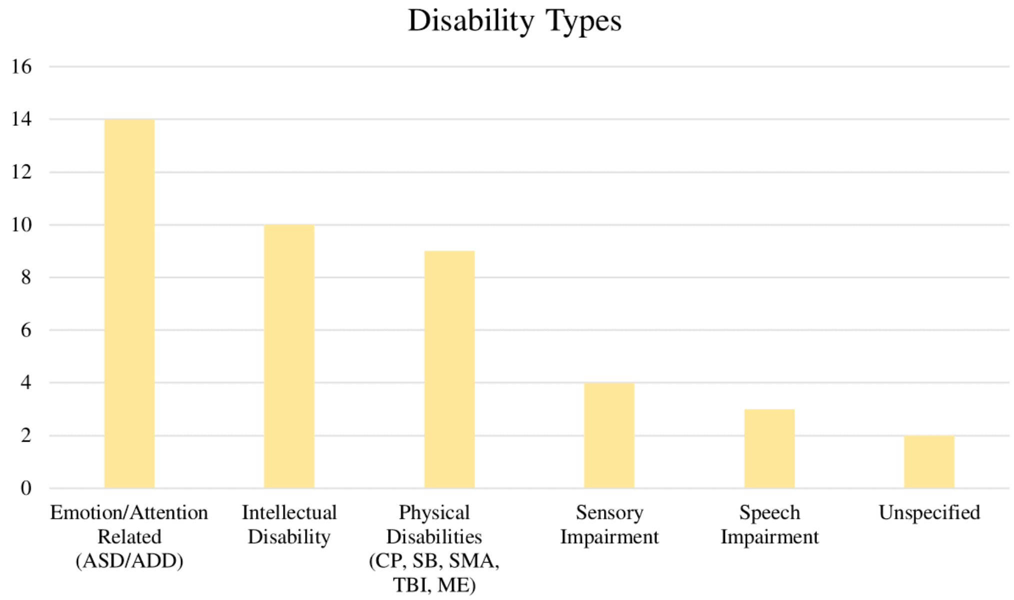

*Figure 3.* Categorization of learner disabilities in the 30 reviewed studies

**Recommendations:** To improve the activity system for the Subject component, a repository can be created to offer practical guidelines on how to design robot-assisted learning activities for each disability category shown in Figure 3. Such categorization will facilitate the role of special education practitioners in designing the appropriate robotic learning activities for each disability category. For example, the activity design strategies and tools for learners with Physical Disabilities could differ greatly from those for ASD learners. Clustering the design strategies thus ensures that practitioners can have a simple and efficient design and implementation experience using robots as mediating tools to meet the needs of learners in each of the six disability categories we identified.

### 3.2. Technology

The *Technology* component was divided into hardware and instructional design. The hardware consisted of three forms of robots — (a) commercial robot kits (e.g., LEGO Mindstorms), (b) humanoids (e.g., NAO NexGen), and (c) manipulatives (e.g., Bee Bot). In terms of how the hardware was utilized in the designed activities, robot kits were used as an animal or vehicle character whose movements or behaviors were programmed and designed by the participants, whereas humanoids served as either a learning companion or an in-class tutor.

Figure 4 shows that the most common use of robots (50%) was as a vehicle, animal, or manipulative designed and programmed by learners as a technological product (e.g., Wright, Knight, Barton, & Edwards-Bowyer, 2019). The robots were manipulated through different channels such as sound generating device or switches (e.g., Bargagna et al., 2018; Disseler & Mirand, 2017). The second use of robots was a learning companion (47%), where humanoids acted as playable peers who trained learners' academic skills (e.g., Cook et al., 2005; Freitas et al., 2017), communication (e.g., Lee & Hyun, 2015; Saadatzi et al., 2018), and social and interactional capabilities (e.g., Albo-Canals et al., 2018; Huijnen, Lexis, Jansens, de Witte, 2016). The humanoids also achieved therapeutic effects on movements (e.g., Khaksar et al., 2019; Van den Heuvel et al., 2017b) and daily functions (e.g., Park & Kwon, 2016). The third use of robots was a humanoid in-class tutor (3%) that instructed learners how to communicate appropriately through text messaging (Pennington et al., 2014).

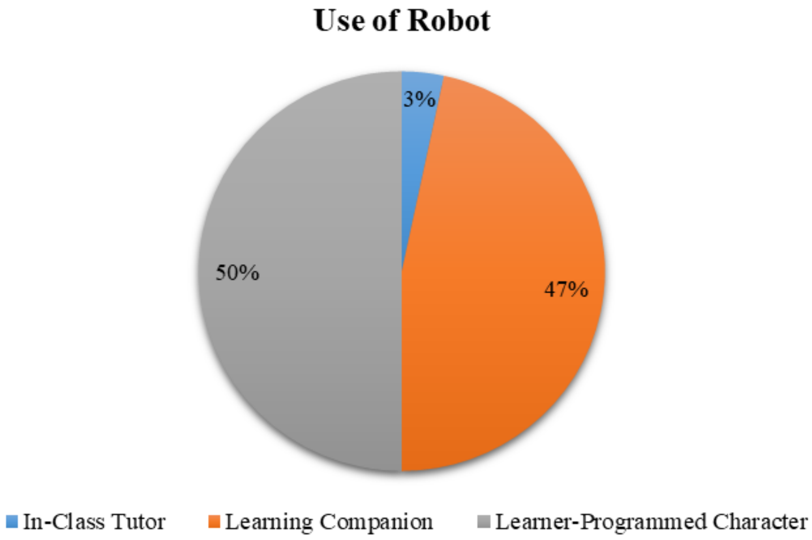

*Figure 4.* The role of robot in the 30 reviewed studies

The use of robots was consolidated by domain-specific instructional strategies and activities. First, the instructional design of robotic programming employed strategies, such as problem solving (e.g., Karna-Lin et al., 2006; Ludi & Reichlmayr, 2011; Yuen, Mason, & Gomez, 2014), multimodal interaction and feedback (e.g., Howard et al., 2012, Dorsey et al., 2013), competition (e.g., Dorsey et al., 2013; Howard & Park, 2014), and inquiry (e.g., Disseler & Mirand, 2017; Jung, Lee, Cherniak, & Cho, 2019) to enhance the learning process and heighten learners' motivation. Personalized adaptations strategies were also used to accommodate learners' needs (Lindsay & Hounsell, 2016). For instance, physical adaptations made use of a magnifying app for visually impaired learners; cognitive adaptations included the use of prompts, reminders, and simplified instruction in reading; and social adaptations included anxiety reduction and pairing of cooperative learners (Lindsay & Hounsell, 2016). Lastly, inquiry (Disseler & Mirand, 2017) and interactional games were used for academic learning (Freitas et al., 2017).

Strategies for language and literacy development included scripted play and talk (Lee & Hyun, 2015; Van den Heuvel et al., 2017a; Van den Heuvel et al., 2017b); affective learning (Lee & Hyun, 2015); self-learning (Lee & Hyun, 2015); robot therapy (Lee & Hyun, 2015); fun elicitations (Huijinen et al., 2016); and social interactional learning made use of picture-verb matching and picture-sentence matching (Park & Kwon, 2016). To train executive functions and visuo-spatial skills, strategies such as learning-by-doing and learning-by-thinking were used to enhance visual-working memory and intellectual abilities (Bargagna et al., 2018). Finally, to improve general functions and motor skills, social interactional learning and play-like activities were employed to improve movement and social interaction skills (Park & Kwon, 2016; Van den Heuvel et al., 2017b).

Table 3 shows the five derived learning domains and activity types in robot-assisted special education. Robotic Design and Programming activities (e.g., Disseler & Mirand, 2017; Howard, Park, & Remy, 2012; Ludi & Reichlmayr, 2011; Pihlainen et al., 2017) included building a robot (Karna-Lin et al., 2006) programming for robotic movements (Bargagna et al., 2018) and executions (Howard et al., 2012), connecting modules (Adams & Cook, 2013), teaching robots to draw (Howard & Park, 2014), and constructing robot cars (Disseler & Mirand, 2017). Activities focusing on the design of robotic actions provided participants the experience technological development through co-ideation with adults (Bertel et al., 2013) or designing challenges (e.g., moving down a maze; Ludi & Reichlmayr, 2011). The design and programming activities also effectively increased the participants' motivation, concentration, communication, and activeness as they learned to create interesting technology constructs (Karna-Lin et al., 2006).

Robotic Play activities made use of different robotic roles to create interaction effects. A child-size and doll-like humanoid helped autistic children participate in multi-modal social interactions (Huijnen et al., 2016). A companion robot also successfully provided learners with interactive scenarios for turn-taking, goal achievement, and sensory interactions (Van den Heuvel et al., 2017a). Similarly, a humanoid provided therapy and communication skill building through robotic-play scenarios that enabled robotic control through vocal commands or sensor pressing (Van den Heuvel et al., 2017b) or through telepresence in classroom or home settings for fostering relatedness (Culen et al., 2019).

For Literacy Development in science, math, languages, and social studies, learners practiced sight words with a truck-like robot character (Saadatzi et al., 2018) through Question and Answer, Counting, and Sequencing Events during story reading (Encarnação et al., 2017; Jordan et al., 2013). Exploration and Ideation activities, on the other hand, made use of the Bee Bot Robot and Cubelets (Jung, Lee, Cherniak, & Cho, 2019) to help high-functioning ASD learners participate in non-sequential inquiry. The sensor-embedded Cubelets are manipulative blocks assembled and programmed by learners with ASD. Additionally, a therapeutic humanoid was used for co-ideation and co-creation in parent-child participatory learning (Bertel et al., 2013).

Kinesthetic Tasks focused on motions, gestures, and dance. Humanoids (e.g., ZORA and Nao NextGen) were used to facilitate the kinesthetic development via leg movement exercises and dancing with songs (Van den Heuvel et al., 2017b). The robots also rewarded learner behaviors, provided learning cues, and induced active learning. The kinesthetic activities engaged learners more effectively than conventional classroom activities (Hedgecock et al., 2014). Finally, Artistic Creation activities used LEGO robotic products. Learners created music by drawing on a screen using the LEGO Education EV3 Mindstorms Kit (Pihlainen et al., 2017).

*Table 3.* Learning domains and activity types supported by different robotic hardware

| Learning domains | Activity type | | | | | |
|---|---|---|---|---|---|---|
| | Robotic Design & Programming (*n* = 20) | Robotic Play (*n* = 14) | Literacy Development (*n* = 8) | Exploration & Ideation (*n* = 4) | Kinesthetic Tasks (*n* = 3) | Artistic Creation (*n* = 2) |
| Academic Development in STEM or Humanities (*n* = 17) | *n* = 10<br>Robot Kits | *n* = 3<br>Humanoids | *n* = 1<br>Robot Kits | *n* = 3<br>Humanoids<br>Manipulatives | | |
| Communication & Social/Interactional Skills (*n* = 17) | *n* = 3<br>Robot Kits | *n* = 7<br>Humanoids | *n* = 5<br>Humanoids | | *n* = 2<br>Humanoids | |
| General Operation & Movement (*n* = 9) | *n* = 2<br>Robot Kits | *n* = 3<br>Humanoids | *n* = 2<br>Humanoids | *n* = 1<br>Humanoids | | *n* = 1<br>Manipulatives |
| Executive Functions & Perceptual Skills (*n* = 6) | *n* = 2<br>Robot Kits | *n* = 2<br>Humanoids | | | *n* = 1<br>Humanoids | *n* = 1<br>Manipulatives |
| Active Task Engagement (*n* = 2) | *n* = 3<br>Robot Kits | | | | | |

**Recommendations:** Robot-assisted interventions should implement more Exploration and Ideation, Kinesthetic, and Artistic Creation activities (See Table 3) because these types of activities can help learners in special education develop cognitively, emotionally, and behaviorally (Denisova et al., 2019). A recent study on teacher training further shows the importance of implementing creative activity design integrating robots in special education (Coskun, 2020). To fill this gap, more efforts should be devoted to investigate ways to foster learners with disabilities through creative tasks and kinesthetic engagement. For instance, more teacher training should be provided to improve the design and use of robotic learning activities in special education for better learning outcomes. Moreover, guidelines that aim to improve domain-specific skills (e.g., Academic Development or General Operation and Movement) should be offered for each of our proposed disability category in a repository of standard practices for robot-assisted special education.

### 3.3. Object

The objectives of the reviewed studies were to train learners' (a) academic skills in STEM, (b) communication and social interaction skills, (c) general operation and movement, (d) executive functions and perceptual skills, and (e) active task engagement. Table 3 shows that while many studies focused on training academic, communication, and social interaction skills, few studies investigated learners' active task engagement (n=3). This finding points to the need to shift the focus of research objectives in robot-assisted special education toward self-initiated learning.

**Recommendations:** Robot-assisted special education practitioners should formulate more learning objectives to increase active task engagement and create a positive impact on the career readiness for learners with disabilities. This will help them gain self-efficacy and positivity when going into a career related to computers and robotic technology (Ludi & Reichlmayr, 2011). One way to achieve this is to incorporate group-based, hands-on activities during workshops and camps with designs that allow them to share ideas and learn from one another.

### 3.4. Rules

The *Rules* component focused on Intervention Procedure and Performance Measures. The studies consistently followed strict implementation procedures, including (a) recruitment of target learners based on selection criteria, (b) training the professionals on using robotic technology for instruction, (c) training the learners how to use the robots in the learning activities, (d) establishing baseline conditions, (e) designing the experiment or case study, (f) implementing the learning activities, and (g) evaluating the learners' performance based on well-defined measures.

It was essential to apply precise quantitative and qualitative Performance Measures in robot-assisted special education due to challenges, such as the heterogeneous nature of participant profiles, small sample sizes, and the absence of control groups in many of the studies. Both objective (e.g., Howard, Park, & Remy, 2012) and subjective (e.g., Dorsey et al., 2013; Howard et al., 2012; Karna-Lin et al., 2006) measures were used to evaluate learners' goal attainment (Cook et al., 2005), engagement (Hedgecock et al., 2014), language development (Encarnação et al., 2017), interest and efficacy (Ludi & Reichlmayr, 2011), or neuropsychological and cognitive development (Bargagna et al., 2018).

Based on the coding scheme in Table 2, seven types of Performance Measures were identified (See Figure 5), Academic Performance ranked first and measured STEM performance in robotic design and programming (e.g., Howard et al., 2012; Jung et al., 2019), mathematics (Encarnação et al., 2017; Freitas et al., 2017), and physics (Disseler & Mirand, 2017). Active Task Engagement ranked second. This measure concerned the extent to which learners actively participated in the activities and stayed focused on task with persistence (e.g., Freitas et al., 2017; Hedgecock et al., 2014; Karna-Lin et al., 2006). Communication/Language Use and Social/Interactive Performance ranked equally as the third most commonly adopted measures. Communication/Language Use focused on skill performance in conversation, word use, and Question-and-Answer (e.g., Encarnação et al., 2017; Lee & Hyun, 2015); and Social/Interactive Performance assessed participation during play, turn-taking, and collaboration in social interactions (e.g., Albo-Canals et al., 2018; Huijnen et al., 2016; Van den Heuvel et al., 2017a).

The Rules component bears several challenges. First, since every learner had different disabilities, it was difficult to maintain a single set of Intervention Procedures or Performance Measures. Second, many learners could not directly communicate their user experience and feedback, the practitioners could not collect their real experience and opinions about the robotic interventions. Third, in terms of outcome evaluation, traditional pen-and-paper tests have been used to assess the learners in the reviewed robot-assisted special education studies. However, the lengthy process of these tests may discourage learners with disabilities (Disseler & Mirand, 2017).

**Recommendations:** Special education practitioners should explore the potential of robots as evaluators or assessment tools, and use them in creating new implicit methods for assessing outcomes in special education assisted by educational robots. For instance, it is possible to make robots act as evaluator by collecting log history of learners' interactions and analyze them to provide assessment on active task engagement, motivation, and learning outcomes. Based on the assessment results, it is possible to offer adaptive learning paths in robot-assisted special education to learners in a specific disability category. This is a potential research niche, as no previous study has reported the use of adaptive learning in robot-assisted special education.

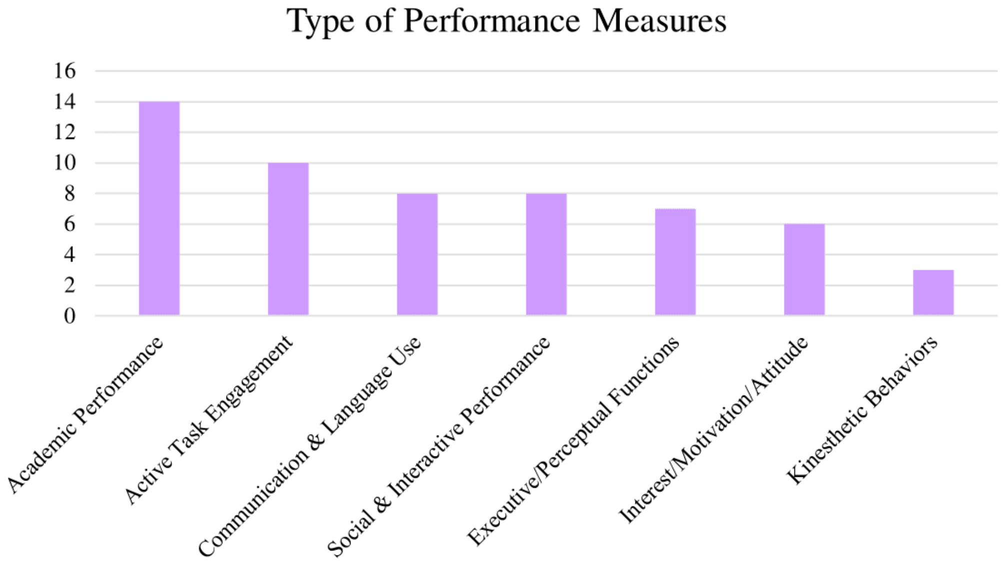

*Figure 5.* Classification of performance measures used in the 30 reviewed studies

### 3.5. Community

The *Community* component included special education professionals, parents, family, friends/classmates, and learners with disabilities. All of the reviewed studies involved special education professionals, namely, therapists, researchers, educators, facilitators, or designer in the interventions, however, only three studies involved the participation of parents or family members in the interventions (Pihlainen et al., 2017; Lindsay & Hounsell, 2016); and only one study involved friends or classmates of adolescents with Chronic Fatigue Syndrome (Culen et al., 2019). This shows a need for more parental participation in robot-assisted special education as the participation of parents in these activities can lead to better learning experience and outcomes (e.g., Lindsay & Hounsell, 2016). As for the variety of special education settings, the interventions were carried out at special education general schools or special education schools ($n$ = 16), rehabilitation/care centers or hospitals ($n$ = 9), robotics camps/workshops ($n$ = 3), educational technology laboratories ($n$ = 2), technology clubs ($n$ = 1), or at home ($n$ = 1).

A number of challenges for the Community component were identified. First, some robot-assisted intervention settings did not adequately fulfill professional and parental expectations of a safe, pleasant, and inclusive learning environment. Second, when interventions were conducted in an inclusive environment, real constraints were reported by mainstream teachers who practiced inclusion education (Encarnação et al., 2017), including difficulty with managing the different time frames between typically developing and learners with disabilities during robotic learning activities. Third, the adaptability of the mediating environment was considered low, and higher robot autonomy was expected in therapeutic scenarios.

**Recommendations:** In response to the challenges, several recommendations have been put forth. First, designers of robot-assisted interventions should involve parents during the process of creating a safe and pleasant environment for learners with disabilities to work toward their professional goals. This would help the participants live more independently in the future (Huijnen et al., 2016). Second, with the goal to foster an inclusive environment, robot-mediated learning environments should provide not only educational benefits, but also social inclusion. This would ensure long-term success of the learners with disabilities in the mainstream society (Ludi & Reichlmayr, 2011). Third, robots should have adaptive functionalities to meet individual learner needs along the intervention timeline. It would be desirable to design robots based on users' attitudes, perceived adaptability, perceived usefulness, intention to use, perceived enjoyment, and trust (Huijnen et al., 2016). Finally, concerning organizational capacity, more research should be conducted to investigate the extent to which learning institutions and schools can accommodate the needs of learners with disabilities.

### 3.6. Division of labor

The *Division of Labor* was among (a) learners with disabilities, (b) special education professionals, and (c) parents. Firstly, the learners were involved in different ways by (a) receiving training on using robots to complete learning activities, (b) participate in robot-assisted learning activities to improve specific skills or knowledge, and (c) providing individual feedback on robot-assisted learning. Second, special education professionals engaged in (a) recruiting participants, (b) training the professionals and the learners, (c) designing and implementing the intervention/learning activities, (d) facilitating learners throughout the robot-assisted learning process, (e) creating performance measures and evaluating the learning outcomes, and (f) providing feedback on the use of robots in special education. Third, parents were involved in different ways. Only in a few studies did they play active roles in the design of robotic solutions by providing support on technology development and feedback on the effectiveness of the robot-mediated instruction (e.g., Pihlainen et al., 2017). In some studies, parents participated by looking at the learners' designed products (Lindsay & Hounsell, 2016) or taking care of them prior to, during, and after the robot-mediated learning process.

A gap was identified with respect to learners' participation in the design of learning activities and interventions. No study that involved the learners with disabilities in the design or planning process for the robot-assisted interventions. This was a missing element that might have affected the suitability of the designed activities and implementation procedure, as it was necessary to cater to the learners' disability differences in special education (Encarnação et al., 2017; Huijnen et al., 2016).

**Recommendations:** In terms of instructional design and implementation, more responsibilities should be shifted to parents and learners in the activity system. The parents can be more actively involved in the intervention process and play active roles such as co-designing a programmable character using robot kits. Special education practitioners who plan to design robot-assisted interventions can also invite learners with their target disability types to participate in pilot tests to help practitioners improve their activities before actual interventions. Such co-creation and co-participatory design of target robotic learning activities will make the learning experience beneficial for the learners.

### 3.7. Outcome

Outcomes based on specific performance measures are discussed based on disability categories and perceptions of special education professionals. Specifically, educational robots made learners with Emotion/Attention Related disabilities (ASD, ADD) more motivated and engaged in learning. They also helped them acquire knowledge from several domains, including cause-effect concepts, robotic programming skills, and acquisition of sight words. Additionally, educational robots enhanced the communication and social interaction of learners with Emotion/Attention Related disabilities. For learners with Intellectual Disability, not only did educational robots motivate them, but also they enhanced their knowledge, skills and intelligence quotient.

For learners with Physical Disabilities, educational robots helped them become more physically active through body movement tasks. Robots also facilitated these learners' goal attainment, as well as their movement, communication and robot programming skills. Learners with Speech Impairments, on another note, perceived learner-robot interactions as effective language learning treatment. Moreover, educational robots made learners with Sensory Impairments highly interested and confident in learning. For instance, visually impaired learners improved their programming as well as visual skills through maze navigation (Dorsey et al., 2013). Finally, for learners who suffered learning difficulties due to Unspecified Disabilities, educational robots enhanced their learning motivation, concentration, social, and teamwork skills.

Perceptions of special education professionals revealed the effectiveness and benefits of adapting the robotic program for the needs of target learners (e.g., Lindsay & Hounsell, 2016). The professionals approved of the suitability of the robotic play content related to daily life and the valuable potential of using specific educational robots (e.g., KASPAR) for working on therapeutic and educational goal attainment (Huijnen, Lexis, & de Witte, 2016).

One contradiction concerned whether robots should replace humans. Many special education experts expressed their ethical consideration about the use of robots as a social interactive agent. They disapproved of the absence of a human therapist in robot-mediated environments (Lee & Hyun, 2015), indicating the inability of robots to provide natural responses outside of script content. Additionally, different views on whether the robot-mediated environment adequately fulfilled their expectations of a safe, pleasant, and inclusive learning environment were identified (Huijnen et al., 2016). Another issue was the amount of time and effort spent on choosing suitable robots based on their appearance in order to appeal to learners with disabilities.

**Recommendations:** First, researchers should investigate appropriate appearances of educational robots (e.g., human-like, toy-like, or animal-like) and variability in their facial expressions based on the needs of different disability categories. Adapting the robot to individual learner needs along the intervention timeline is also recommended. Special education practitioners should create robot-assisted special education standards about the treatment frequency, duration, and robots' roles in scaffolding social interactions to ensure that robotic interventions scaffold social interaction skills among learners (e.g., ASD learners) toward interactions with real humans. Moreover, it would be desirable to design the robots based on users' attitudes, perceived adaptability, perceived usefulness, intention to use, perceived enjoyment, and trust (Encarnação et al., 2017; Huijnen et al., 2016). Professional training for instructors and staff on such matters will help to improve robot-assisted special education (Huijnen et al., 2016).

## 4. Conclusion

In order to understand the process involved in robot-assisted special education and the role played by its various stakeholders, this systematic review probed into the design, implementation, and outcome of robot-assisted special education research through the perspective of Activity Theory. Major components of the robot-assisted learning activity system were analyzed, including (a) learners with disabilities, (b) robots supported by instructional design, (c) target skills, (d) intervention procedure and performance measures, (e) community of special education professionals, parents, and learners, (f), division of labor among learners, special education professions, and parents, and (g) learning outcomes. The analysis showed that practitioners need to align robot-mediated instructional design with disability categories of target learners, learning strategies, and robot types. This connection among the activity components would create more effective learning and generate greater benefits for learners with disabilities. The review further provided recommendations based on each activity component so that existing challenges, gaps, and contradictions can be minimized in future design and implementation of robot-assisted interventions in special education.

Several limitations should be acknowledged. First, the review consisted of a small number of studies due to the stringent inclusion criteria. Although many articles were retrieved initially, after full-text screening, only 30 studies qualified as our data. However, the small set of data allowed us to reach saturation during the coding to sufficiently address the research questions. Another limitation was the absence of gender as a factor. Only a few studies (e.g., Encarnação et al., 2017; Van den Heuvel et al., 2017b) provided information about the gender of the learners.

The findings contribute to the research fields of special education and robotic technology by providing directions for research design and implementation of robotic-assisted special education. Specifically, more robot-assisted activities should aim to foster creative and kinesthetic skills. Future research may aim to (a) develop general guidelines across learning domains in addition to domain-specific guidelines (e.g., skills in STEM or Humanities, Social/Interactional Skills) for each disability category (e.g., Emotion/Attention Related, Intellectual Disabilities, Physical Disabilities, Social/Interaction Disabilities) and b) designing career preparation activities to help learners with disabilities build an autonomous future life.

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## Supplementary materials

Tables S1, S2, and S3 can be found on
https://drive.google.com/file/d/1jmjSQH4qodvD_czpuP18ehds_7him0zB/view?usp=sharing