Research in Science Education (2022) 52:927–947
https://doi.org/10.1007/s11165-021-10029-3

Multimodal Creative Inquiry: Theorising a New Approach for Children's Science Meaning-Making in Early Childhood Education

Sarika Kewalramani[1,2] · **Nikolay Veresov**[1,2]

Accepted: 17 September 2021 / Published online: 4 November 2021

Abstract

This paper discusses how multimodal creative inquiry might be conceptualised and implemented for children's meaning-making in science. We consider Halliday's (1978) and Vygotsky's (1987, 2016) theoretical ideas for showing how the most important characteristics of social semiotics are connected to imagination, play-based and creative inquiry for children's science meaning-making. Qualitative data was analysed from two preschool classroom video observations of 40 children's playful interactions with technologies, such as robotic toys, semiotic artefacts, two teachers' reflective journal documentation and children's artefacts. Findings show children participate and discuss elements of scientific concepts in inquiry-based dialogues and make sense of science concepts whilst becoming creators of multimodal representations arising from their interests and curiosity. The semiotic resources that operate through technologies such as apps provide a medium for creative inquiry affording communication spaces and multimodal (visual, haptic [digital touch], text) meaning-making around everyday science phenomena. Practical implications lie in upskilling educators' integration of semiotic resources such as robotic toys and deploying a multimodal creative inquiry approach for reconfiguring children's science learning opportunities in early childhood educational practices.

Keywords Creative inquiry approach · Children's science meaning-making · Early childhood science · Multimodal semiotic resource · Vygotsky and Halliday integrated theoretical model

✉ Sarika Kewalramani
sarika.kewalramani@monash.edu

Nikolay Veresov
nikolai.veresov@monash.edu

[1] Monash University, Melbourne, Australia

[2] Faculty of Education, Monash University, Peninsula Campus, Moorooduc Hwy, Frankston, Victoria 3199, Australia

Introduction

This paper theorises how multimodal creative inquiry might be conceptualised and implemented for children's science meaning-making as a way to advance the application of the characteristics of social semiotics (by using robotic toys) connected to children's multimodal meaning-making. Concerns have been raised by early childhood (EC) educators with the watering down and simplification of science concepts that are explicitly taught in the primary and secondary years of schooling and can have a negative impact on children's science educational trajectories (Hirsh-Pasek et al., 2009). Challenges and concerns raised by early childhood educators about how to introduce elements of science to children inform a deficit model of practice (Fleer, 2019; Kewalramani & Havu-Nuutinen, 2019). Fleer's (2019) seminal work in EC science education highlights how imaginative play promotes children's scientific learning. Fleer's study underpins play pedagogy, which is a strength of early childhood educators, and through the model of scientific playworlds, the study propagates how imaginary situations can be developed into scientific narratives. Nevertheless, this area of EC science education is still under researched and needs to build nuanced theoretical and pedagogical understandings in relation to the application of multimodal semiotic resources to support children's science meaning-making process (Sundberg et al., 2019; Yelland, 2018).

Today, young children come into the classroom already able to access information about the world around them with a swipe of a finger, further exacerbating the pedagogical problem of knowing what children need to know. More recently, studies are beginning to show, for example, how children's interactions with technologies support their learning in reading (Kucirkova, & Falloon, G. (Eds.)., 2016), mathematics and engineering concepts (Sullivan & Bers, 2016), and science circuitry concepts (Peppler et al., 2019). However, with technology becoming the mediator of children's everyday contexts, there have been very few studies which consider the multimodal nature of technologies which act as semiotic tools and how multimodal play and creative inquiry might enable children to make sense of everyday scientific phenomena. In this paper, we draw upon the seminal work of Tang and Moje (2010) who argue that children make meanings during a multimodal discourse and show how such discourse provides support to children's science learning (Tang et al., 2014). We aim to investigate how technologies such as robotic toys can be used as a semiotic tool within a multimodal creative inquiry approach to support children's science meaning-making in early childhood education. We consider Halliday's (1978) and Vygotsky's (1987, 2016) theoretical ideas to show how the most important characteristics of social semiotics are connected to children's imagination, multimodal representation of science concepts, and using creative inquiry for children's science meaning-making in EC educational practices.

Introducing Science in Early Childhood Education: the State of the Art

Research studies in science education in primary and secondary contexts are grounded in well-established pedagogies children's science learning (Tang et al., 2011, 2014; Williams et al., 2019). Authors in the primary-secondary schooling sector have already shown how students develop a better scientific understanding of scientific phenomena by using and alternating between a variety of representations (Hubber et al., 2010; Tang et al., 2014). Hubber et al. (2010) have suggested that students' 'representational resources' can help them make sense of new science concepts. Similarly, Tang et al. (2011, 2014) demonstrate how drawings can be a mode of sign-making and reasoning that affords new understandings of science concepts and how drawings can contribute to the emergence of scientific literacy. However, that is not the case in EC science educational practices. To date, only a few pioneering studies have documented young children's development of science concepts. For example, several years of seminal research have informed our understanding of children's science conceptual development through the model of scientific playworlds (Fleer, 2019). Yelland's (2016, 2018) work around multimodal learning with the use of technologies has shown how EC educators can facilitate mutually engaging interactive contexts for children's digital literacies. Havu-Nuutinen et al.'s (2017) study has shown pre-primary pupils' drawings as representations of early conceptions of water in the context of technology, society and awareness of sustainability issues. Sundberg et al.'s (2019) large-scale Swedish study in 14 preschools has identified examples of 'multidimensional science teaching', where intentional teaching intertwines children's science learning with multiple dimensions of children's lives, such as emotions, fantasy, play and aesthetic modes of expressions. Such studies show the promising nature of how emergent science learning can occur in early childhood classrooms, together with fostering children's dispositions of learning such as scientific discovery over learning of facts. However, the use of technologies as a multimodal semiotic resource to pave the way for promoting children's creative inquiry and multimodal ways of making sense of science concepts still remains under-researched. To address this research gap, the current study's focus is two-fold: firstly, to theorise the multimodal creative inquiry using social semiotics as an approach to understanding children's science meaning-making process, and secondly, to investigate how educators and children use robotic toys (semiotic resource) within the multimodal creative inquiry approach, and whether the use of the semiotic resource shape children's meaning-making in science. In the next section, we theorise how a multimodal creative inquiry approach might be conceptualised to understand children's science meaning-making.

Multimodal Creative Inquiry (MCI) Approach as a Proposed Solution for Science Meaning-Making

Yelland (2018) defines multimodal learning as the application of more than one mode (multimodality) for learning that offers rich learning experiences for young children. For example, multimodalities can include linguistic (text-based), visual, kinaesthetic (digital touch), aural and spatial (movement) modalities. Children make sense of their real world and the scientific phenomena available in their everyday environments through such multimodal ways. Further when children use technologies for play, they make sense of their natural learning environments by blending the real world and their imagination via digital experiences (Arnott et al. 2020; Arnott & Yelland, 2020). As new technologies continue to evolve and emerge, as artefacts of the twenty-first century, multimodal ways of learning when used together with three dimensional materials can provide children with multiple forms for science meaning-making. To date, there is limited research on how technologies, specifically robotic toys, can be used in age appropriate ways with children as a multimodal semiotic tool. The robot's codable characteristics such as prompting (e.g., talking [speech and language], movement, digital touch) provide an interesting stimulant for children to engage in creative inquiry. The children are more likely to easily learn to code the robot to perform a set of actions, which can then aid in meaning-making when children are engaged in inquiring about a particular scientific phenomenon under investigation with their peers. Next, we explain what is creative inquiry in the context of multimodal learning using robotic toys as a semiotic resource.

We define creative inquiry (CI) as a collectively created way of introducing science to children through child-adult and child-child interaction and communication, which can be both verbal and non-verbal interactions. Existing methods of presenting science to children very often do not correlate with the capabilities and potential of children in the early years. For example, the introduction of scientific concepts too early can lead to children simply remembering the words associated with these concepts without understanding their content and meaning. They often simply verbally reproduce what they remembered in response to a teacher's question, without showing creativity and independent thinking. By employing a creative inquiry approach, there is an opportunity to change science learning from 'science-centred' to 'child-centred' inquiry, from 'reproduction-focused' to 'creativity-focused' and from 'learning-focused' to 'development-focused'.

Multimodal creative inquiry is a concept that does not replace play-based learning per se, the former rather augments play and makes it transformative as children move back and forth within their physical and digital play spaces (Edwards, 2021). For Yelland (2018), whilst studying children's play with technologies as semiotic resources and the interactions during play, the focus should be on play being multimodal, rather than solely on digital aspects of multimodality. In essence, as part of the creative inquiry process, children are co-working with each other and the teachers to construct knowledge and shape the semiotic resource being used (robotic toys in the current study) for meaning-making. Creative inquiry is a way to launch conversations with children that happens through questioning, communication of ideas, problem posing and problem solving all of which occurs as part of children's socially constructed play (Chang, 2012; Jewitt et al., 2016). In the next section, we present the integrated theoretical approach inspired by Halliday (1978) and Vygotsky (1987, 2016) to theorise the multimodal creative inquiry approach for children's science meaning-making.

Theorisation of CI: Vygotsky Meets Halliday

Vygotsky

Vygotsky's cultural-historical theory presents an important theoretical background for conceptualising the creative inquiry approach. Play is the leading activity in early childhood which means it determines most important developmental changes in children, creating the Zone of Proximal Development (ZPD) for the child (Vygotsky, 2016). Play is a creative activity characterised by the 'imaginary situations' the child creates during play experiences. In play and through play the child learns, discovers the world and receives new knowledge and experiences. However, this does not mean that the direct inclusion of science education into the child's play automatically guarantees a positive developmental result. As Vygotsky claims (Vygotsky, 2016), children's play develops according to its own laws, and artificial interventions might extinguish the play rather than sustain it. Therefore, we consider the triad 'play-learning-interactions of present and ideal forms' as the first set of cultural-historical theoretical tools for the analysis of the method of creative inquiry. According to Vygotsky, we can present this triad as related to what is known in theory as the concept of the social situation of development (SSD) (Vygotsky, 1998). The teacher, introducing a specifically constructed CI into the child's play, creates a unique social situation of development, opening up the creative inquiry for everyday and scientific concepts.

The second general tool for theorisation is the idea of interaction between 'everyday' and 'scientific' concepts. In Vygotsky's approach, creative inquiry happens when scientific concepts interact with child's everyday concepts. However, this is only possible if this happens in a series of specially organised interactions between everyday concepts and scientific concepts. In our research, we consider the process of interaction of the everyday and scientific concepts as an example of what Vygotsky defined as an interaction of the ideal and present form

> The social environment is the source for the appearance of all specific human properties of the personality gradually acquired by the child or the source of social development of the child which is concluded in the process of actual interaction of «ideal» and present forms. (Vygotsky, 1998, p. 203)

The general theoretical model of CI as a method to understand children's science meaning-making might be as shown in Fig. 1.

The model shows interrelations of the triad 'play - learning - interactions of an ideal and present forms' with the concepts of everyday and scientific concepts and the social situation of development where play (as a component of CI) is conceptualised as a specially created SSD. Learning of science is viewed as an interaction of the ideal and real forms (everyday and scientific concepts) within the children's play situations. In other words, the specificity of CI is characterised by play and learning, where play is a specially created social situation of development together with the adult in the child's natural learning environment, where science learning is a specific form of interaction of ideal and real forms (everyday and scientific concepts).

In our study, children's process of concept formation is considered as an interaction of the everyday and scientific concepts that is a specific form of interaction of the ideal and present forms of concepts. It challenges the traditional methods of teaching science, when scientific concepts are introduced directly to a child by an adult (teacher). Everyday concepts in a child are based on limited empirical experience, and therefore, there might be

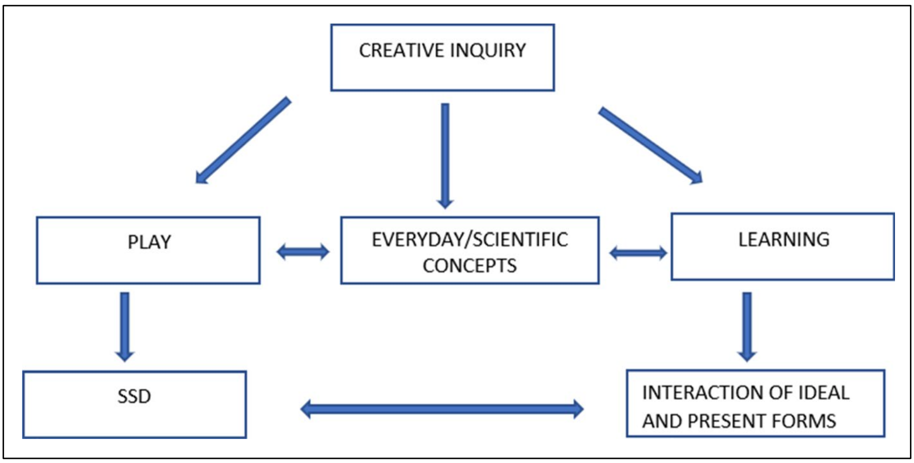


Fig 1 Theoretical model of creative inquiry based on Vygotskian concepts

children's misconceptions with respect to the scientific concepts. However, they are the present forms that are necessary for the process of concept formation (Vygotsky, 1987, 1998). Scientific concepts, on the other hand, are ideal forms that should appear in a child at the end of development of the present forms. Hence, the role of the teacher is to organise the interaction of these present and ideal forms. In other words, within the framework of CI, instead of directly introducing scientific concepts, the teacher (1) builds a dialogue, starting from asking the child how they understand the phenomenon and how the child can explain it—that is, the teacher identifies existing present forms (everyday concepts) in child, and (2) gradually introduces the ideal forms (scientific concepts) as a result of which the everyday (incorrect and limited) concepts are gradually replaced or at least progress the child's understanding of the scientific concept in developmentally appropriate manner. Moreover, the method of CI and use of multimodal semiotic resource creates a system for the child, where everyday concepts (present forms) are indicators of the level of the child's actual development, and scientific concepts (ideal forms) are indicators of the level of potential development. Through explicit questioning and dialogic interactions, the teacher makes the process of concept formation and meaning-making child-focused and development-centred. Everyday concepts although might be misconceptions with respect to the scientific concepts should not be ignored by the teacher as they correctly reflect the actual level of a child's development—the level from which the movement to scientific concepts should begin with.

The multimodal CI approach, therefore, becomes a child-centred method if creative thinking emerges from the child's play as an integral part, not as something that is brought to play artificially from outside. CI would then be 'creativity-focused', not aimed at reproducing what the child learns but rather encouraging the child's interest and curiosity. Finally, creative inquiry would be development-focused and not merely a learning process. Through a series of interactions between scientific and everyday concepts, creative inquiry would create a science meaning-making for the child.

However, a problem arises—how can multimodality and the multimodal character of science meaning-making might be reflected in this theoretical model and could be further theoretically framed. This important aspect of the creative inquiry cannot be covered by the model based on Vygotsky's approach. At this theoretical crossroads, it seems to us, Vygotsky meets with Halliday. This will be explored in the following section.

Vygotsky Meets Halliday: Improving the Theoretical Model

In the social semiotic theory (Halliday, 1978), multi- and inter-modality in meaning-making is one of the strongest and the most powerful concepts. Opposite to traditional semiotics that considers meanings as impersonal and fixed in the text itself, social semiotics does not assume that texts produce exactly the meanings and effects that their authors hope for. Hodge and Kress's (1988, p. 12) seminal work on social semiotics suggests 'it is precisely the struggles and the uncertain outcomes that must be studied at the level of social action, and their effects in the production of meaning'. What is central to multimodality is the concept of the semiotic resources as the actions, materials and artefacts people use for communicative purposes. They include, for example, physiological (vocal apparatus, the muscles to make facial expressions and gestures) or technological ones like pen and ink, computer hardware and software—together with the ways in which these resources can be organised. What is important is that semiotic resources have the potential to enable meaning-making by acting as a set of affordances based on their possible and creative uses. When the semiotic resource (a technology-based robotic toy in the case of this study) is actualised in concrete social contexts by children and adults, their use is subject to some form of a semiotic regime (Van Leeuwen, 2010).

Social semiotics theory allows us to take a fresh look at the role of semiotic resources and multimodality in meaning-making and thereby significantly enrich understanding of the creative inquiry approach of introducing science to children. We particularly focus on technologies such as robotic toys as a semiotic resource to consider that meaning-making should follow from the child's direct experiences as well as extend these experiences to the degree the child becomes curious about science through the modalities (haptic [digital touch], motion, visual, text) afforded by the robotic toys. These toys boost children's motivation and creative imaginative abilities to grasp abstract science concepts (Kewalramani et al., 2020a, b; Peppler et al., 2019).

However, is there any possibility for combining the ideas of Vygotsky and Halliday without the risk of falling into a theoretical mess? In other words, do the ideas of the social situation of development and play fit into Halliday's theory of social semiotics. Kellogg and Shin (2018) provide a holistic and complete picture of the conceptual complementarity of both of these approaches. Like Vygotsky, Halliday understands that creative inquiry and meaning-making refers to age-specific zones of childhood and that accomplishments in meaning-making is central to child development and not simply learning in general. Vygotsky 's social situation of development is his way of describing the contexts that according to Vygotsky are the source of development. But we can also see that by giving a central role to language use and language functions, there is an alignment between Vygotsky's social situation of development with the kinds of observations that Halliday has been making in the accomplishments of meaning-making by focusing on representational and experiential meaning-making (Kellogg & Shin, 2018).

In relation to the process of the formation of everyday scientific concepts via multimodal interactions and meaning-making with semiotic resources, two of Halliday's works are extremely important for our purpose, *The Language of Early Childhood* (Halliday, 2004) and The *Introduction to Functional Grammar* (Halliday & Matthiessen, 2014). Thus, in relation to the meaning-making process afforded by a semiotic tool, Halliday and Matthiessen present three ways for representational and experiential meaning-making to occur in children: (1) elaboration, (2) extension and (3) enhancement (Halliday & Matthiessen, 2014, p. 461-487). In some sense, these ways of making meaning and/or communicating meaning through language use or through multimodal (text, movement, visual) representations might be considered as a child's meaning-making initiated within the CI process, therefore, allowing us to make an analysis of the multimodal CI approach from the child's perspective.

Finally, Halliday's social semiotics suggests an important shift in the analysis from representational forms of collective meaning-making (based on reproducing knowledge) to experiential forms (based on shared experience) as a social/interpersonal line of meaning-making (Hasan, 2005). As we see, Halliday's approach, which includes multimodality, semiotic resources, ways of meaning-making (elaboration, extension and enhancement) and inter-personal meaning-making, does not contradict Vygotsky's approach; on the contrary, it might significantly enrich it and might help to theorise some specific aspects of multimodal creative inquiry as the approach to understanding children's science meaning-making process. This allows us to improve Fig. 1 theoretical model to Fig. 2.

Figure 2, as our study's integrated theoretical model, depicts that children communicate their science meaning-making through representational thinking and experiential

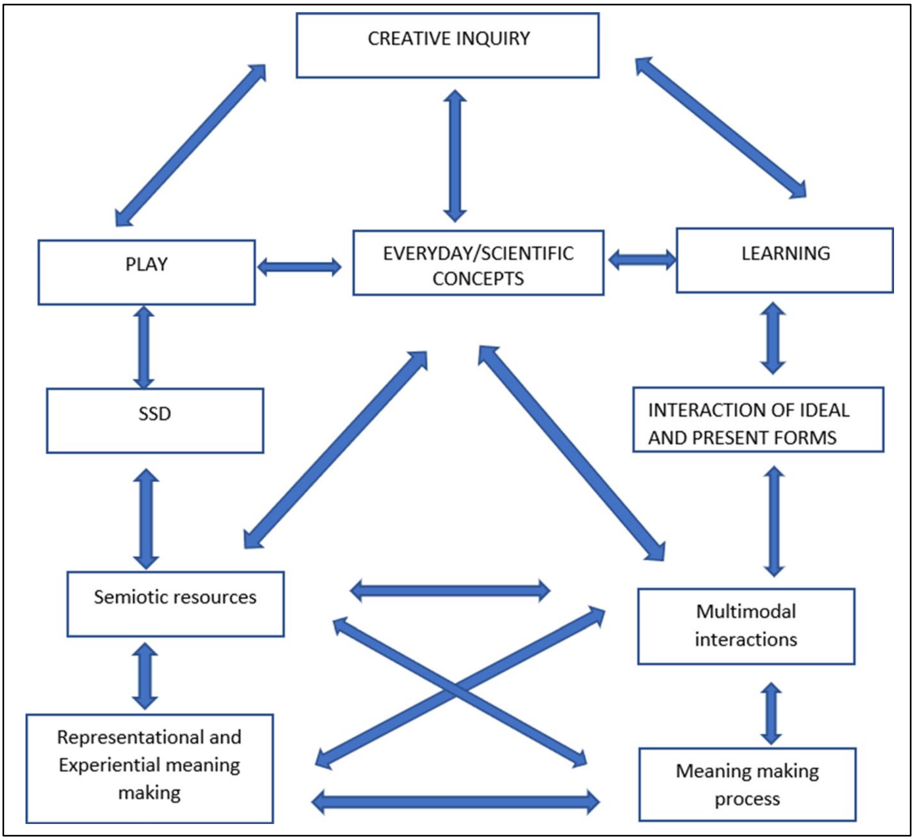


Fig 2 Multimodal creative inquiry approach using semiotic resources for science meaning-making

learning whilst they collaborate in social situations. When the semiotic resource (robotic toy operated using an app or a remote control) is placed meaningfully in children's learning environment, it becomes a multimodal resource fostering robot-child, child-child and child-adult type interactions. The interactions that the child has with the robot is dependent upon the child, and their agency and imagination. The process of meaning-making is not linear, and the multimodal interactions can be reciprocal (two-way process), when the child encounters the physical and virtual worlds whilst making sense between the everyday and scientific concepts being investigated in an experiential manner. The reciprocal interactions and communication between the child and the robot as well as the manipulation of the robot to perform certain tasks acts as a natural stimulus to provide the child with a novel and unique experiential play-based experience that serves as an opportunity and a source for representational thinking.

Further, according to Halliday and Matthiessen (2014), when children play with multimodal semiotic resources (robotic toys in our case), representational and experiential science meaning-making process occurs through (1) elaboration—when children's scientific thinking is represented through narratives, dialogues and stories; (2) extension—when children's scientific thinking is visualised and generalised through their representations such as drawings and constructions of multimodal artefacts; and (3) enhancement—when children's thinking goes beyond visualisation and generalised representations, but rather conscious awareness of how the science phenomena around them works, thus improving scientific literacy, science vocabulary in their memory and affective thinking—all important for initiating and understanding children's science meaning-making process within SSD and multimodal creative inquiry.

Methods and Context

A design-based research (DBR) approach was employed, which is apt for small-scale educational research projects involving collaboration between educators, children and researchers (Jetnikoff, 2015; Morgan, 2013). The DBR approach allows for investigation of possibilities for educational improvement as an educational experiment by bringing about new forms of learning, to generate, trial and refine changes to pedagogy (an integration of multimodal semiotic resources such as robotic toys in our case) in order to study them. In our study, the DBR approach involved adapting the evidence-based framework (Kewalramani & Havu-Nuutinen, 2019), encompassing the five steps concerning the essential pedagogical features for developing children's creative inquiry—planning, targeted question-driven inquiry, building children's inquiry skills, teacher-child and peer-peer interactions and assessment/review of children's learning (see Table 1 for the integration and implementation of play the toys). These five steps as part of the DBR approach were guided by our study's integrated theoretical model (Fig. 2) to offer an ideal methodology to understand children's science meaning-making process using the robotic toys as a semiotic resource.

Context

This study took place in two kindergarten classrooms where we introduced different types of robotic toys (see Table 2) that can function in different styles (tangible and hybrid). Recruitment was sought by sending emails to the centre directors of three kindergartens situated in culturally diverse communities in the metropolitan suburbs of Melbourne, Australia. The participating kindergarten's director then recommended teachers who were interested and willing to take part in the research. Prior to starting the project, the first author made two visits to give a brief introduction of the use of various robotic toys involved in the project, thus playing an alternated role of an instructional leader and instructional support.

We examined two classrooms (N=20 children in each class; total N=40 children), in which the children played and interacted together with their teachers (N=2) and co-educators (teacher assistant; N=2) in an everyday living settings (Denzin & Lincoln, 2011). Data collection ranged from 3 to 6 months of a continuing study with the integration of the robotic toys as seen in Table 2 (Qobo, Coji, Cosmo, Botley, LEGO Boost constructed robot called Vernie). The kindergarten was inspired by the early childhood educational philosophies from Reggio Emilia approach. Hence, the teachers employed a child-centred approach and considered children as communicators and collaborators in their own learning. Because the kindergarten was affiliated to an International Baccalaureate school, they also integrated units of inquiry into their curriculum. During the time when the project was conducted, the unit of inquiry focus was about 'How the world works' and the teachers planning revolved around the curriculum focus of providing appropriate inquiry starters to engage children in concepts within their everyday environment. Because the robots have

Table 1 Pedagogical steps for the integration of the toys as semiotic resources during play experiences

Step	Activity/actions
Planning	The overall play with the robotic toys was co-created by the researchers, teachers, co-educators and children, thus employing a **child-centred** approach. The robots were introduced intentionally by the researchers. However, the **inquiry and experiential learning** process was driven by some of the children wanting to go on an imaginary adventure with their robot **(creating social situations of development** with the robots).
Targeted question-driven inquiry	The children were playing with battery-operated robots (Botley and Kibo) and using block play to build ramps and roadways for their robots to travel **(multimodal play)**. Consequently, children were asked, 'What makes the robot move? What problems would they encounter if the battery dies? And how will they solve the problem?' During this step, the children were specifically introduced to iPad app-operated robots such as Coji and Lego Boost Vernie that can show emojis (laughs, dance, and children can programme stories and tasks for the robot to perform). Similar questions were asked for children to observe the difference between how and why Botley and Coji worked.
Building children's inquiry skills	The teachers used effective questioning techniques at the beginning of each session. Open-ended inquiry questions involved 'We've been talking about all the places that Qobo and Coji could go and what they might like to do?'
Teacher-child and peer-peer interactions	Within the reciprocal teacher-child instructions and targeted question-driven inquiry, consideration was given to the children's **construction of artefacts** for the city in which the robot family can survive and live happily, specifically in relation to their ideas about electronics and electricity. Within the peer-peer and **multimodal interactions** (sensory iPad touch, visuals, sounds, texts), children role played, problem solved and ensured their robot family survived in their city by constructing solar panels to save the batteries from dying.
Assessment/review of children's learning	Post-whole class discussions about what children had constructed and **narrative stories** about their robotic adventures enabled a deeper and richer learning experience, fostered through a **creative inquiry approach.**

'human-like' attributes (e.g. move and talk) that are demonstrated by the ways the robots respond to stimulus such as coding commands provided by the child, the teacher intentionally asked questions to spark child's imagination, curiosity and awareness of how robots operate. The teachers' 'hidden agenda' was underpinning the unit of inquiry for children to investigate the impact of scientific and technological advances on society and on the environment (International Baccalaureate Organisation, [IBO], 2012).

Data were generated through video observations of children's and educators' play experiences (15 weeks of total observations with 1 h per week of play session = 15 h is being reported in the context of this paper) and informal conversations with the children during the play experiences. Field notes were used to document the context, routines and procedures, alongside the building of rapport between the children, the teachers and co-educators. Data also encompassed the weekly reflective journals that were a part of teachers' documentation of the play experiences.

Table 2 List of robotic toys used in the research

Robotic Toys	Description
 **COSMO**	This is a wireless robot. It includes a robot and cubic that can be programmed and moved around. It is controlled by a tablet-based app. However, it also can be controlled by touch or voice and face recognition.
Botley 	This is a battery-operated remote-controlled floor robot. It can be coded using the remote control to say few words such as Hi and make silly noises for example.
Coji by Wowee 	A wirelessly controlled robot that children can programme in order to move using emoji language and physical actions.
 **Qobo the snail**	Qobo operates using different puzzle cards with different meanings that are recognised by a reader when placed under the Qobo robot. These cards allow the robot to move, sing, interact or blink.
Vernie—LegoBoost Bot 	Introduces basic coding skills to younger children. With Boost, children create and animate different constructions (e.g. a robot, a cat or a car that can be coded to move, talk, sing, dance).

In the context of this study, it was crucial to be in proximity to the classroom reality, to observe the educators' practices, instructions and interactions as well as hear the viewpoints of the educators and children about the play with robotic toys. As such, our project was guided by the key characteristics of participatory research (Groundwater-Smith et al., 2014). The first author took the role of a participant-observer in collecting the data. Parents were advised that the play sessions were voluntary, that is, children would not be forced to participate. Approval was granted by the authors' University Research Ethics Committee and relevant local authorities including the Victorian Department of Education. Ethical procedures were ensured to seek educators, parents' and children's consent, being mindful that the observation sessions were not intrusive, and the interview questions suited the educators' pedagogical needs and opinions and respected their professional knowledge and experiences. Pseudonyms have been used for the kindergarten settings and their respective educators and children. The EC settings' safe Internet use policy was followed at all times.

Data Analysis and Findings

Critical to this study was a multimodal creative inquiry approach to building children's meaning-making around the everyday science phenomenon of electricity. Throughout the play experiences, the teachers and researchers questioned the children using open questions that encouraged the children to think of possibilities for representing their science ideas (everyday concepts) in the form of drawings, stories, role plays and constructed artefacts—all necessary in a multimodal creative inquiry approach.

We analysed the data using our integrated theoretical framework (Fig. 2). This framework lists a series of characteristics and interactions associated with the MCI approach. For example, interactions include children posing a question or a problem, response to a question, communicating a solution to the problem, hands on experimentation (coding the robot) to solve a problem and representing thinking through drawings and constructions (blending of physical and digital modalities). Using Wright's (2011) analytical approach to the notion of semiotic units in our analysis, we investigated the meanings made within children's play based and experiential interactions with the semiotic resource (robotic toys). Semiotic units are combinations of signs that are used to express a complete meaning (Wright, 2011). Firstly, we sifted through the data and deduced examples that were relevant to children's social situations of development created using the robots as a semiotic resource and children's experiential play techniques and representations of science concepts. Next, we mapped the theoretical concepts used to approach the data, which in this case was represented by the alignment between the above outlined play interactions and characteristics associated with MCI approach. Lastly, we mapped the elements of modalities (haptic [digital touch], visual, tactile, use of words) and how these modalities aided children's meaning-making of science. Researcher checks as well as member checking (one of the teacher participants was invited to view the data examples) were used to ensure the validity of the interpretations made (Cho & Trent, 2006). Member checking allows the participants on whom the research has been done so they could indicate their agreement or disagreement with the way the researchers represented the data interpretation. Re-examining the findings through the method of member checking allowed for representation of the realities of the play experiences and provides reliability in the findings (Ary et al., 2010; Cho & Trent, 2006).

The data is presented in the form of narratives, which aim to unveil children's imaginative thinking about the science concept in hand, problem-solving interactions and communication of ideas and experiences as stories. The interpretation of children's stories is done both explicitly and implicitly, to make meaning from not only what was spoken or from the child's drawings, but also the meaning behind their words, constructed artefacts or what remained unspoken (Clandinin, 2007). This involved closely analysing children's interactions with their peers and teacher as well as the 'virtual' interactions with the robot that fostered science meaning-making. We report our observations primarily from a group of children who were involved in constructing solar panels and a battery world to save their robots from 'dying'. All names have been de-identified as per the University's ethics guidelines.

Case 1: Meaning-Making of Electricity and Batteries that Make Robots Work

The teacher wanted to intentionally introduce the children to the robotic toys about the inquiry topic 'How the world works'. The below group discussion was framed using the robots as the central theme to provoke children's imagination and ideas about their everyday world and environment around the children. In the introductory play session involving Coji and Botley, the robotic toys, the teacher (T) initiated open-ended questions:

T: What would Coji and Botley like to do?
Charlie: Draw
Mini: Have a house made of blocks (then discussed what the houses could be made of)
Ava: Made of junk

Mini: Made of electricity and pipes

Some children said robots can go in a little car.
At one point, the children coded Coji to make some water noises:

William: He wants to go for a swim!
Teacher questioned: How would he swim?
Ava: He would break because it would get soggy and die.
Charlie: There's poison inside the batteries.
Ava: We don't want to waste the batteries.
T: Why does Coji have a battery?
William: Because he's working

In another group play session, teacher prompts and children respond:

T: What do you like about robots?
Mini: They move, they have remote controls
T: What do you mean by control? How Botley moves (Talking about the remote)
Charlie: Uses electricity
William: Has an on/off switch
Charlie: Drones

The discussion then steers in the direction of the construction of drones.

Mini: You can see things without going there

Four children mentioned they had drones and robots at home and the teacher provoked children's creativity to construct drones, remotes and robots and getting some children to bring them in to class to 'show and tell' other children. The below discussion about robots then is mostly linked to the Transformer movie.

Charlie: They *(drones)* have remote control and can go upside down
Mini: My TV has a remote, does that make it a robot?

At the end of the session, teacher asks what the class thinks a robot is:

Ava: Has power/electricity/battery
Charlie: Has remote control
William: There's Apps we can download to control robots. I have one at home.

In this case, CI is child-centred and the inquiry begins from children's everyday concepts about batteries, remote controls and how robots work. These science ideas were evident in children's experiential learning when they were tinkering with the robots' multimodal characteristics (haptic [digital touch] and motion). Children's creative inquiry about why the robots can or cannot work were connected to their imagination and collaborative communication, and as such creative inquiry was 'development-focused' as through the conversation children improved their understanding of how robots work (electricity, remote control, batteries). Accordingly, children's careful orchestration of meaning-making and affordances provided by the semiotic resource (robotic toy) enabled their successful elaboration (communication of the concept of electricity through narratives and robotic adventure stories). It is also interesting to note that, within the creative inquiry and multimodal meaning-making process, the teacher as the participant joined in children's social situations, interactions and discussions, thus augmenting the creative inquiry and the imaginary situation created by children using the robotic toy as the semiotic tool. The interaction of the child with the robot is mediated by the teacher and not only dependent upon the child. Table 3 illustrates children's multimodal creative inquiry and science meaning-making process through elaboration—when children's scientific thinking is represented through narratives, dialogues and stories.

Case 2: Continued Meaning-Making of Electricity and Solar Power

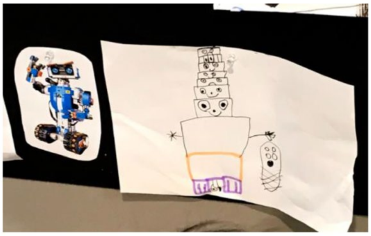
In another play session, another child, Bec, was drawing her robot (see Table 4) in line with her imagination and creativity, representing her thinking about how the robot operates with a battery operated remote control. On another occasion, in continuation with their meaning-making of electricity as an everyday science concept, a group of children constructed a 'battery world' and solar panels for the robots to visit in order to recharge themselves (see Table 4). The following is a play session which includes children's multimodal creative inquiry:

T: Have you heard of solar power?
Ava: They'll have to charge up on their electricity
Eddie: yep, you get it from the sun
Andy: the solar panels get it from the sun. All robots need it.
T: could they tap into the sun from the solar panels? What are they?
Andy: some are on the roof, they are flat and black and they get power from there
Ava: sometimes we take the solar panel on camping and it charges the lights and phone.
William: it could charge your bedroom and other rooms.

Table 3 Children's multimodal creative inquiry and science meaning-making through elaboration

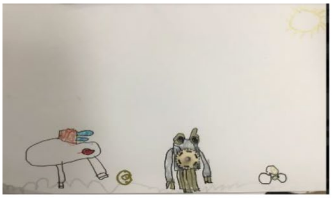
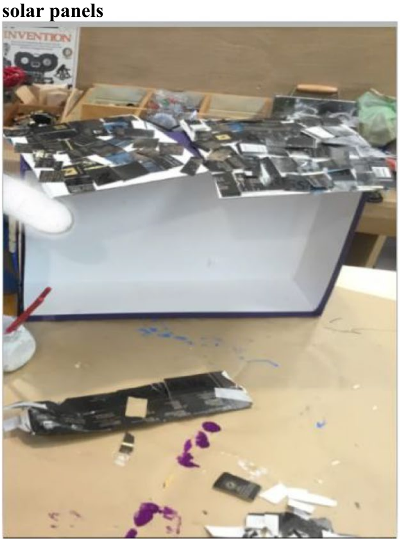
Image	Children's narratives	Links to multimodal creative inquiry and science meaning making process
Robot working through battery-operated remote control 	- The robot is working because it has batteries - They move, they have remote controls - Uses electricity - Imaginary situations such as robots wanting to go for a swim and within which a situation arises that the robot's battery may become soggy and stop working	- Children's play and multimodal characteristics (digital touch and motion) - Social situation development using the robots children make connections to how everyday concepts (remote control, on/off switch, drones) were connected to scientific concepts (battery, remote control, robot works and moves, electricity) - Reciprocal child-child, and child-adult interactions occur enabling sense making of everyday and scientific concepts within the group discussion, narrative dialogues, together with experiential and hands on manipulation afforded by the robot's multimodal characteristics

Table 4 Children's multimodal creative inquiry and science meaning-making through extension and enhancement

Images of children's multimodal 2D/3D representation and experiential learning through constructed artefacts	**Interpretation of image**	**Links to multimodal creative inquiry and science meaning making process**
A robot working with remote control 	- Imagination and creative inquiry represented through 2D drawings showing scientific thinking about how child made sense that the robot works with a battery-operated remote control	- Children's 2D representations demonstrated how they were exploring the use of multiple modes of communication and interactions with the robots which went beyond the dominant use of verbal language (narratives and dialogues) - - Scientific thinking being visualised and generalised through representations such as children's drawings
A Lego robot working with Lego remote control 	- Imaginary situation with the robot being the *centre of children's world* unfolded as a 3D representational by-product of their collective creative inquiry	- Children's science meaning making process through experiential learning using robots that enabled their Lego remote control constructions (representational thinking of batteries and electricity) - - Children's interactions and creative inquiry about a particular scientific phenomenon (solar energy) under investigation with their peers and teacher
A robot working with sun's energy (solar power)	- The creative inquiry process (which was predominantly 'information seeking' to solve a problem) generated children's solution to design and construct a battery world that	- Children's enhancement of science meaning making - conscious awareness of how the science phenomena around them works and can cause damage to the planet

T: I've heard if you use too much electricity
Andy: it will go out and run out and nothing will work
T: I've heard making electricity with coal damages our planet, we shouldn't be using it anymore. You have to dig to get it out. We can use the sun it's there every day.

Table 4 (continued)

 **Robot's battery world being charged using solar panels**  	demonstrates children's abilities to connect *everyday and scientific* concepts - solar panels to recharge robot's battery and that solar panels act as an energy making source for the robots to survive (*affective thinking and scientific literacy)*. - In their interactions and discussions, children making sense that 'making electricity with coal damages our planet, we shouldn't be using it anymore'	(scientific literacy and affective thinking)

Andy: but at night times it's not there
Jo: how can we figure out a plan to use the power from the sun so we don't hurt the planet.
William: the sun shines on the panels
Andy: at night time houses that have solar panels, there lights still work at night time.
Eddie: it's coz of the electricity
Jo: instead of getting it from the sunlight it gets it from the moon light

This example showcases children's experiential learning using the robot as a 'sparking curiosity' semiotic tool that fosters children's extension. Through a series of questions that were 'information seeking' in order to solve the problem of no electricity or too much electricity, the children made connections between the sun's energy as solar power and how electricity can be generated. Children's meaning-making process progresses from their narrative stories about robots working using battery-operated remote control to being extended as evident from their 2D drawings to 3D multimodal constructions (Lego remote control and solar panels as seen in Table 4). The robotic toy being the fulcrum of children's science meaning-making acts as a semiotic technological tool and actively facilitates the creative inquiry process through extension and enhancement. Children's representations of solar panels and remote control were sparked by their sense making of the everyday concept about saving solar energy. Andy's idea that 'all robots need energy' and the subsequent inquiry discussion allowed children's active discovery about the concept of electricity and solar power (everyday scientific concept) to be realised. Table 4 illustrates children's science meaning-making process through extension (when children's scientific thinking is visualised and generalised through their representations such as drawings and constructions) and enhancement (when children's thinking goes beyond visualisation and generalised representations).

Discussion and Conclusions

In this paper, we theorised how a multimodal creative inquiry approach might be conceptualised and we provided examples of its implementation to understand children's science meaning-making. Findings extend Tang and Moje's (2010) and Williams et al.'s (2019) studies in showing that using creative inquiry children make better sense of the explored scientific phenomena (e.g. electricity, how remote controls work, solar power). Children alternate between the created imaginary situations (everyday concepts) using the robotic toy as a semiotic resource and represent their scientific thinking through elaboration (represented through narrative dialogues), extension through drawings and 2D/3D multimodal constructions and enhancement through a conscious awareness of how the science phenomena of remote controls work (batteries can get charged through solar power or else the robot will die, thus improving scientific literacy). This meaning-making process happens through the entanglement between the imaginary play and the children's connections with their physical environment where they actually 'see' and 'sense' the scientific phenomena and concepts under consideration. The pedagogical nature of SSD here is that children are not just left to play with the robots. Rather these are introduced to the children by adults (the teacher) who have their own curriculum agendas and who talk with them in particular, intentional ways, deliberately 'feeding in' topics such as solar energy and sustainability. One of the intentional ways is asking children open-ended questions and information seeking/problem solving questions, whereby the robot as the semiotic resource becomes the central theme and/or character into the children's narratives fostering the creative inquiry and active discovery process. By deploying the multimodal creative inquiry approach, the teacher integrates targeted question-driven inquiry and builds children's inquiry skills, thus scaffolding children's meaning-making of the science phenomena being explored. Henceforth, creating the conditions for children to represent their understanding of everyday science phenomena such as how robots work using remote controls and need energy in the form of batteries and solar panels.

Our study findings demonstrate how teachers could use a variety of pedagogical techniques in building SSDs using robots as semiotic resources such as (1) asking challenging questions about child's everyday concepts, (2) formulating the problem for the inquiry, (3) suggesting or interrogating the solution of the problem, (4) cooperating in solving the problem using robots as the semiotic resource and (5) mapping/drawing the inquiry process. In other words, the teacher deliberately builds the SSD as a specific system of interactions with the children and the robots, as well as encouraging child-child collaborative interactions.

The multimodal creative inquiry approach thus becomes an effective approach in terms of firstly the children's making sense of everyday science concepts, and then how through experiential play, using the semiotic resource, furthers children's representation of scientific ideas through elaboration, extension and enhancement process. Extending previous studies which only considers multimodal representations for meaning-making in science education (Sundberg et al., 2019; Tang et al., 2014; Williams et al., 2019), our study's multimodal creative inquiry approach not only reveals some general empirical features and traits of this method but also acts as a way to support children's making sense of science concepts. This happens because of child-centred and child-driven inquiry, narrative dialogues, multimodal 2D/3D representations which depict children's experiential learning and scientific thinking using the multiple modes afforded by the semiotic resources. We believe that such a multimodal creative inquiry model not only substantiates the effectiveness of CI as a method of science meaning-making, but also reveals the potential of this method.

We continue the debate around the significance of understanding children's play with semiotic resources as 'sparking curiosity'and as an 'experiential' multimodal tool that enables us to become more effective in designing science learning for children in the twenty-first century, thus also steering away from the dangers of schoolification (Hirsh-Pasek et al., 2009; Peppler et al., 2019; Yelland, 2016, 2018). It does not mean that all children should be utilising new technologies, for example, as a semiotic resource whenever they encounter science concepts in their everyday environment and learning journeys; rather that children's interactions with everyday science phenomena should be interpreted as multimodal creative inquiry. Hence, their play should be too. It is through multimodal play affordances that children construct meanings of the scientific phenomena around them and if we want children to confidently and safely make claims and arrive at conclusions about the role of science and new technologies in their lives, we need to allow for both technologies as a multimodal semiotic resource (e.g. spoken words, textual, visual, movement, digital touch) and engagement in child-driven creative inquiry within children's experiential play (Hubber et al., 2010; Tang et al., 2011, 2014).

Our study's implications lie in how teachers can formulate their pedagogical techniques in building the creative inquiry approach. Teachers might apply CI to support the development of children's knowledge about science without using the direct methods of teaching, not as a one off science experiment approach but rather deploying an experiential method of learning science (Hubber et al., 2010). An example of such a pedagogical technique can be:

-Teacher introduces the scientific concepts related to children's everyday concepts.

-Teacher employs creative inquiry to discuss with children using robots for example as a multimodal semiotic resource to generate open-ended, information seeking and problem solving narratives and dialogues as meaning-making tools (interaction between the everyday and scientific concepts).

-Teacher incorporates experiential learning and representational thinking of children's everyday science concepts through elaboration, extension and enhancement.

As a result, (1) the inquiries are creativity-focused (as they happen within the imaginary situations created in children's play and contribute to them); (2) the inquiries become child-centred (as they follow from defining children's everyday concepts enabled through the multimodal semiotic resource and creative interactions with children); and (3) the inquiries are development-focused (as they occur as a process of interaction between the ideal (scientific concepts) and present (children's everyday concepts) forms). A multimodal creative inquiry approach thus creates the special conditions for enabling children to make meaning of everyday science concepts through experiential and representational learning. Further studies are recommended to explore the social underpinnings of the early childhood learning environment as well as the potentialities of the teacher as the pedagogue within the scientific playful learning context. Halliday's views on representational and experiential learning and semantic expansion can be used as a proximal perspective for further studies.

This paper adopted a nuanced approach in firstly theorising what is multimodal creative inquiry underpinning theoretical concepts such as Vygotsky's and Halliday's works on social semiotics. We provided empirical examples based on our qualitative research to showcase how the approach can look in action within children's play with robotic toys in an early childhood classroom setting. However, this paper is not a full source of empirically based case studies. This is a limitation of our study. Further research should focus on using the multimodal creative inquiry approach to investigate the shifts or deepening understanding of the scientific phenomena and concepts in hand.

Acknowledgements Our sincere thanks go to the preschools, educators and children who participated in this study.

Funding This research received funding from Monash University's Early Years Academic Community for data collection.

Declarations

Statement of Data, Ethics and Conflict of Interest The authors acknowledge having no financial interest or benefit arising from the direct applications of their research. Data is owned by the first author, and the project received ethical clearance from the Monash University Human Research Ethics Committee. Informed consent was gained from parents and educators. The photos used in the paper form part of the usual reporting procedures of the centres and are used with permission.

References

Arnott, L., & Yelland, N. (2020). Multimodal lifeworlds: Pedagogies for play inquiries and explorations. *Journal of Early Childhood Education Research, 9*(1), 124–146 https://jecer.org/wp-content/uploads/2020/02/Arnott-Yelland-issue9-1.pdf

Arnott, L., Kewalramani, S., Gray, C., & Dardanou, M. (2020). Role play and technologies in early childhood. In Z. Kingdon (Ed.), *A Vygotskian Analysis of Children's Play Behaviours: Beyond the Home Corner* (pp. 76–92). Routledge

Ary, D., Jacobs, L. C., Sorensen, C., & Razavieh, A. (2010). Introduction to research in education. Engage Learning.

Chang, N. (2012). What are the roles that children's drawings play in inquiry of science concepts? *Early Child Development and Care, 182*(5), 621–637.

Cho, J., & Trent, A. (2006). Validity in qualitative research revisited. *Qualitative Research, 6*(3), 319–340.

Clandinin, D. J. (Ed.). (2007). Handbook of narrative inquiry: Mapping a methodology. Sage Publications.

Denzin, N. K., & Lincoln, Y. S. (2011). The SAGE handbook of qualitative research (4th ed.). Thousand Oaks, CA: Sage

Edwards, S. (2021). Digital play and technical code: What new knowledge formations are possible? Learning, Media and Technology. https://doi.org/10.1080/17439884.2021.1890612

Fleer, M. (2019). Scientific Playworlds: A model of teaching science in play-based settings. *Research in Science Education, 49*(5), 1257–1278.

Groundwater-Smith, S., Dockett, S., & Bottrell, D. (2014). Participatory research with children and young people. Sage. 10.4135/9781473910751

Halliday, M. A. K. (1978). Language as social semiotic: The social interpretation of language and meaning. Laden Edward Arnold.

Halliday, M. A. K. (2004) The language of early childhood. London: Continuum.

Halliday, M. A. K., & Matthiessen, C. M. I. M. (2014). Halliday's introduction to functional grammar. Routledge.
Hasan, R. (2005) Language, society and consciousness. London: Equinox.
Havu-Nuutinen, S., Kärkkäinen, S., & Keinonen, T. (2017). Changes in primary school pupils' conceptions of water in the context of Science, Technology and Society (STS) instruction. International Research in Geographical and Environmental Education, 27 (2).
Hirsh-Pasek, K., Golinkoff, L. E. B., & Singer, D. (2009). A mandate for playful learning in preschool. Oxford University Press, Inc. pp. 5-15.
Hodge, R. and Kress, G. (1988). Social semiotics. Cambridge: Polity Press.
Hubber, P., Tytler, R., & Haslam, F. (2010). Teaching and learning about force with a representational focus: Pedagogy and teacher change. *Research in Science Education, 40*(1), 5–28.
International Baccalaureate Organisation. (2012). The Primary Years Programme. https://www.ibo.org/globalassets/publications/become-an-ib-school/ibpyp_en.pdf
Jetnikoff, A. (2015). Design based research methodology for teaching with technology in English [online]. *English in Australia, 50*(3), 56–60.
Jewitt, C., Bezemer, J., & O'Halloran, K. (2016). Introducing Multimodality. Routledge.
Kellogg, D., & Shin, J. (2018). Vygotsky, Hasan and Halliday: Towards conceptual complementarity. *British Journal of Educational Studies, 66*(3), 287–306. https://doi.org/10.1080/00071005.2017.1364695
Kewalramani, S., & Havu-Nuutinen, S. (2019). Preschool teachers' beliefs and pedagogical practices in the integration of technology: A case for engaging young children in scientific inquiry. *Eurasia Journal of Mathematics, Science and Technology Education, 15*(12). https://doi.org/10.29333/ejmste/109949
Kewalramani, S., Palaiologou, I., & Dardanou, M. (2020a). Children's engineering design thinking processes: The magic of the ROBOTS and the power of BLOCKS (electronics). *Eurasia Journal of Mathematics, Science and Technology Education*. https://doi.org/10.29333/ejmste/113247
Kewalramani, S., Palaiologou, I., Arnott, L., & Dardanou, M. (2020b). The integration of the Internet of Toys in early childhood education: A platform for multi-layered interactions. *European Early Childhood Education Research Journal*. https://doi.org/10.1080/1350293X.2020.1735738
Kress, G. (1993). Against Arbitraiiriness: The social production of the sign as a foundational issue in critical discourse analysis. *Discourse and Society, 4*(2), 169–193.
Kress, G. (2009). Multimodality: A social semiotic approach to contemporary communication. Routledge.
Kucirkova, N., & Falloon, G. (Eds.). (2016). Apps, technology and younger learners: International evidence for teaching. Routledge.
Morgan, A. (2013). Proof of concept': Beginning to use design-based research to improve science literacies for middle years learners. *Australian Journal of Language and Literacy, 36*(1), 3–16.
Peppler, K., Wohlwend, K., Thompson, N., Tan, V., & Thomas, A. (2019). Squishing circuits: Circuitry learning with electronics and playdough in early childhood. *Journal of Science Education and Technology, 28*(2), 118–132. https://doi.org/10.1007/s10956-018-9752-2
Sullivan, A., & Bers, M. U. (2016). Robotics in the early childhood classroom: Learning outcomes from an 8-week robotics curriculum in pre-kindergarten through second grade. *International Journal of Technology and Design Education, 26*(3). https://doi.org/10.1007/s10798-015-9304-5
Sundberg, B., Areljung, S., & Ottander, C. (2019). Opportunities for education for sustainability through multidimensional preschool science. Nordic Studies in Science Education. https://doi.org/10.5617/nordina.6237
Tang, K.-S., & Moje, E. (2010). Relating multimodal representations to the literacies of science. *Research in Science Education, 40*, 81–85.
Tang, K.-S., Tan, S. C., & Yeo, J. (2011). Students' multimodal construction of work-energy concepts. *International Journal of Science Education, 33*, 1775–1804.
Tang, K., Delgado, C., & Moje, E. B. (2014). An integrative framework for the analysis of multiple and multimodal representations for meaning-making in science education. *Science Education, 98*(2), 305–326. https://doi.org/10.1002/sce.21099
Van Leeuwen, T. (2010). Introducing social semiotics. Routledge.
Vygotsky, L. S. (1987). The collected works of L.S. Vygotsky (Vol. 1). Plenum Press.
Vygotsky, L. S. (1998). The collected works of L.S. Vygotsky (Vol. 5). Plenum Press.
Vygotsky, L. S. (2016). Play and its role in the mental development of the child. *International Research in Early Childhood Education, 7*(2), 3–25.
Williams, M., Tang, K.-S., & Won, M. (2019). ELL's science meaning making in multimodal inquiry: A case-study in a Hong Kong bilingual school. *Asia-Pacific Science Education, 5*(1), 1–35. https://doi.org/10.1186/s41029-019-0031-1
Wright, S. (2011). Meaning, mediation and mythology. In D. Faulkner & E. Coates (Eds.), *Exploring Children's Creative Narratives (pp. 157–176)*. Routledge.

Yelland, N. J. (2016). Tablet technologies and multimodal learning in the early years. In S. Garvis & N. Lemon (Eds.), *Understanding digital technologies and young children (pp. 122–138)*. Routledge.

Yelland, N. J. (2018). A pedagogy of multiliteracies: Young children and multimodal learning with tablets. *British Journal of Educational Technology, 49*(5), 847–858. https://doi.org/10.1111/bjet.12635

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.