The action-sentence compatibility effect (ACE) a benchmark finding for embodiment - A meta-analysis

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Highlights

- Meta-analytic outline of the action-sentence compatibility effect (ACE)
- Compilation of ACE studies with similar study setups as in Glenberg & Kaschak (2002)
- The overall effect size for the ACE was very small but significant
- Delay occurred as moderator variable in the ACE study setup
- Publication bias in the ACE literature was revealed

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Abstract

The embodied account of language comprehension has been one of the most influential theoretical developments in the recent decades addressing the question how humans comprehend and represent language. To examine its assumptions, many studies have made use of behavioral paradigms involving basic compatibility effects. The *action-sentence compatibility effect* (ACE) is one of the most influential of these compatibility effects and is the most widely cited evidence for the assumptions of the embodied account of language comprehension. However, recently there have been difficulties to extend or even to reliably replicate the ACE. The conflicting findings concerning the ACE and its extensions lead to the discussion whether the ACE is indeed a reliable effect or whether it might be the product of publication bias or other distorting research practices. In a first step we conducted a meta-analysis using a random-effects model. This analysis revealed a small but significant effect size of the ACE ($d = .129$, $p = .007$). A second meta-analytic approach supports these findings of the existence of an ACE (Fisher's method: $\chi^2 = 124.379$, $p < .001$). Furthermore, the task-parameter Delay occurred as a factor of interest in whether the ACE appears with positive or negative effect direction. This meta-analysis further assessed for potential publication bias and suggests that there is bias in the ACE literature.

keywords: Embodied cognition, language comprehension, action simulation, action-sentence compatibility

1 Introduction

When it comes to the question how humans comprehend language, researchers nowadays debate two contrasting accounts. One of these accounts is often referred to as the traditional view of language comprehension. It acts on the assumption that cognitive processes are abstract, arbitrary, and amodal. This traditional view claims that language and sensorimotor processes are operating in separate systems and are using rather different underlying principles and representations. Therefore, language processes are regarded as being separate from sensorimotor processes. As a result, language processes are not directly grounded in the experience of the physical world (Fodor, 1975, 2000; Kintsch, 2008; Pylyshyn, 1984). In contrast, an alternative account of language comprehension emphasizes the tight interconnection between language and the sensorimotor system and argues that language is grounded in perception and action. This account is often referred to as the embodied or grounded model of language processing. The latter account has gained more and more attention in the last two decades, not only in the field of language comprehension but across various research fields within human cognition (Glenberg, 2010) e.g., number processing (Fischer, 2012) or working memory (Shebani & Pulvermüller, 2013). For language comprehension, embodied accounts assume that people understand linguistic information by means of language-induced mental simulations of sensorimotor experiences. Comprehending a sentence in the framework of embodiment means to mentally simulate the described situation by activating the appropriate sensorimotor experiences (Barsalou, 1999; Fischer & Zwaan, 2008; Masson, 2015; Strozyk, Dudschig, & Kaup, 2019). These sensorimotor experiences are assumed to stem from prior interactions with the physical world involving the described objects, situations and events. In other words, this account postulates that during language learning, children typically encounter words while they simultaneously experience the word's referent in the real world. For example, a child might hear the sentence "Look at the horse" and simultaneously see, smell, feel, and hear the horse. These various sensorimotor experiences are then assumed to become associated with the word "horse" via repeated co-occurrences. Later when the

word “horse” is perceived in a situation where no real horse is present, the word “horse” can be understood via the reactivation of these sensorimotor experiences.

Numerous neurophysiological and behavioral studies have provided evidence for the embodiment framework in language comprehension (for review see Jirak, Menz, Buccino, Borghi, & Binkofski, 2010; Meteyard, Rodriguez Cuadrado, Bahrami, & Vigliocco, 2012). Neuroimaging and EEG-studies have shown that there is a considerable overlap between brain areas activated during language comprehension and those activated during the actual sensorimotor interaction. For example a study by Hauk, Johnsrude, and Pulvermüller (2004) showed that during the perception of words with face-, arm-, and leg-relation such as “lick”, “pick”, or “kick” brain areas are activated which are also activated during the actual movement with the tongue, fingers, or feet. Many other studies showed such an overlap in brain areas for various other senses, for instance for “smell”, by showing that reading the word “cinnamon” activates olfactory brain areas (González et al., 2006). Besides the neurophysiological studies, the embodiment view of language comprehension is supported by behavioral studies. Typically, these behavioral studies are based on the argument that if language falls back on sensorimotor processes, then language processing should interact with sensorimotor processes in behavioral setups. Specifically, language should activate related sensorimotor processes, and therefore facilitate or hinder subsequent sensory or motor processes that are similar to the linguistically implied situations. The most prominent effect of this type is the so-called *action-sentence compatibility effect* (ACE), which is nowadays cited 2563 times on google-scholar (19th January 2021), typically as core evidence in favor of embodiment.

The ACE was initially introduced by Glenberg and Kaschak (2002). Originally, the ACE was observed in an experiment in which participants read sentences that implied an action toward or away from the body. The linguistic material consisted of sentences like, “Open the drawer” as a toward sentence because it entails an action toward the body, and “Close the drawer” as an away sentence because it implies an action away from the body. There were two types of sentences, imperative sentences (“Put your

finger under your nose”; “Put your finger under the faucet”) and transfer sentences. The transfer sentences consisted of concrete toward and away sentences, which described a transfer of a physical item (“Courtney handed you the notebook”; “You handed Courtney the notebook”) and of abstract toward and away sentences which contained a nonphysical transfer (“Liz told you the story”; “You told Liz the story”). Additionally, the stimulus set contained sentences that were nonsensical. The material of nonsense sentences also consisted of imperative sentences (“Boil the air”) and transfer sentences “Joe sang the cards to you”. The participants were presented with a random mix of sensible and nonsense sentences and were asked to evaluate these sentences as being sensible or not. Responses were given via a button press on a specially created button box. Three buttons (near, middle, far) differed in their distance to the participant’s body and required a motion toward or away from the body for responding. More specifically, participants pressed the middle button to initiate sentence presentation. In the yes-is-near condition, participants were asked to respond yes (the sentence is sensible) by moving the index finger from the middle button to the near button (making a movement toward the body). For a no response (the sentence is not sensible) participants were to move the finger from the middle button to the far button (movement away from the body). In the yes-is-far condition, the response directions were reversed. As dependent variable, the time between sentence presentation and release of the middle button was recorded. The ACE manifests itself in a significant interaction between the direction implied by the sentence and the direction executed for response. Glenberg and Kaschak (2002) showed that response times in the sensibility-judgment task is shorter in compatible trials (implied direction is toward the body and response direction is toward the body; implied direction is away from the body and response direction is away from the body) than in incompatible trials (sentence direction mismatches the response direction). In the years following the first publication of the ACE effect, a comprehensive range of different studies has investigated the ACE effect with similar experimental settings (see the section “Is the ACE Robust?” in Papesch (2015)) as well as with a vast variety of variants thereof

(Anderson & Spivey, 2009; Fischer & Zwaan, 2008; Garcia & Ibanez, 2016).

1.1 Variations of ACE

In one variation of the original ACE, a different action dimension was manipulated in the sentences and responses. For instance, instead of toward or away arm movements, studies by (Kaup, De Filippis, Lachmair, de la Vega, & Dudschig, 2012; Lachmair, Dudschig, de la Vega, & Kaup, 2016) applied up vs. down arm movements.

Experiments with the up-down dimension for instance used stimulus material with reference to the vertical axis. More specifically, the sentence “Anna looks to the sky” refers to a location in the upper part of the vertical space or “Anna looks to the ground” refers to a location in the lower part of the vertical space. Accordingly, the response box was mounted vertically with the response buttons “up”, “middle”, and “down”, requiring an upward-downward movement for responding (Kaup et al., 2012; Lachmair et al., 2016). Further variations looked at actions involving clock vs. counterclockwise turning movements (Claus, 2015; Taylor & Zwaan, 2008; Zwaan & Taylor, 2006). For instance, a study by Zwaan and Taylor (2006) presented participants with sentences such as “Jim tightened the lug nuts” involving a clockwise turning movement or “Liza opened the pickle jar” involving a counterclockwise turning movement. To judge the sensibility of the sentences, participants rotated a knob either clockwise or counterclockwise. Finally, there are studies that manipulated the effector with which an action is performed. As stimulus material in these types of studies, researchers presented hand-related (e.g., “to grasp”) vs. foot-related (e.g., “to walk”) action verbs, nouns with the lexeme “hand” or “foot” (e.g., “handbag”, “footprint”) or nouns describing an object that is usually handled with the hand or with the foot (e.g., “cup”, “stirrup”). For responding, participants pressed a button with the hand or tapped at a foot pedal with the foot (Ahlberg, Dudschig, & Kaup, 2013; Dalla Volta, Gianelli, Campione, & Gentilucci, 2009; Klepp et al., 2017). Other examples of variation in the dimension involve backward vs. forward-leaning body postures (Zwaan, van der Stoep, Guadalupe, & Bouwmeester, 2012), nodding vs. shaking head

movements (Moretti & Greco, 2018), open vs. closed hands (Melloni et al., 2015; Cardona et al., 2014), different types of functional and volumetric gestures (Bub & Masson, 2010, 2012), pressing vs. turning movements (van Dam, Rueschemeyer, Bekkering, & Lindemann, 2013) and many others.

In addition to these studies looking into the interaction between language and action, there are studies investigating interactions between language and perception. In these studies, the presented sentences still implied a toward or away movement, but instead of responding with a toward or away movement, participants responded by a simple button press but simultaneously perceived a visual or auditory stimulus conveying motion toward or away from the body. In compatible conditions, the direction of the motion described in the sentence matched the direction of motion perceived by the visual or auditory stimulus whereas in the incompatible conditions, the two directions mismatched (Kaschak et al., 2005; Kaschak, Zwaan, Aveyard, & Yaxley, 2006).

A further modification of the original ACE paradigm is employed in studies with priming procedures investigating the reverse direction of influence (sensorimotor task followed by language processing). In a study by De Scalzi, Rusted, and Oakhill (2015), participants pressed two buttons one after the other, requiring an arm movement either toward or away from themselves. After that, the toward or away sentence was presented, and the participants' task was to judge the sensibility of the sentence via a toward or an away arm movement. In another variant of this setup, the presentation of the linguistic material was preceded by the task of moving several beans from one jar to another by means of either a toward or an away movement. These priming studies show that a movement can actually influence the comprehension of language (Glenberg, Sato, & Cattaneo, 2008; Havas, Jenvey, Shilling, & Nathan, 2010) which seems to provide a rather strong evidence in favor of the idea that language comprehension involves simulating experiences.

1.2 Study set of the meta-analysis

The central focus of our meta-analysis is on the original ACE from Glenberg and Kaschak (2002). Because the original ACE is often seen as one of the core empirical evidence in favor of the embodiment account of language processing and therefore it is interesting to clarify how strong the empirical evidence speaks for this specific effect. We thus focused on studies involving either the original study setup or a direct follow-up investigating the ACE in the narrow sense. More specifically, we selected studies for our meta-analysis which examined the ACE on the toward-away dimension using sentences as stimulus material and an arm movement for responding. Still, there is quite some variation within the set of studies we included. In the following sections, we will discuss the different variables that vary across the included ACE paradigms. Deviations from the original ACE study from Glenberg and Kaschak (2002) will be explicitly mentioned.

1.2.1 Task.

The included studies vary in the task which participants undergo during the experiment. In the original study by Glenberg and Kaschak (2002), participants judged the sensibility of the sentences by pressing one of two buttons. This sensibility judgment task is in fact the most common task in this meta-analysis (Bergen & Wheeler, 2005, 2010; De Scalzi et al., 2015; Gianelli, Farnè, Salemme, Jeannerod, & Roy, 2011; Glenberg, Sato, Cattaneo, Riggio, et al., 2008; Gould & Michaelis, 2018; Lugli, Baroni, Gianelli, Borghi, & Nicoletti, 2012; Papesh, 2015; Schwarzkopf, Weldle, Müller, & Konieczny, 2011; Vinson, Perniss, Fox, & Vigliocco, 2017). In a further variation participants also judged the sensibility of the sentences but this time all nonsensical sentences included a pseudoword (“You feaped the mirror”), analog to the lexical decision task where participants categorize stimuli as word or nonword (van Dam & Desai, 2017). Thus, in this case, the judgment does not strictly require sentence-level processes but can be solved at the word level. In further studies the sensibility judgment task was combined with a go/no-go task design. Participants were asked to press the button only if they thought the sentence was sensible (yes response). If they thought the sentence was nonsensical, they had to refrain from responding and had to

remain on the middle button. During each trial, a cue appeared and indicated which button the participant should press (near or far) if the sentence made sense to them (Diefenbach, Rieger, Massen, and Prinz (2013) Borreggine and Kaschak (2006)).

In addition to these tasks involving semantic aspects of the sentences to cue the response, other studies used more perceptual kind of cues, like a color change, a moving stimulus, or the appearance of a particular letter. In these experiments, the stimulus material still consisted of sentences that implied an action toward or away from the body. In the color change task, participants were asked to respond to a color change with a release from the middle button and a press of the near or the far button, depending on the color. For example, the color red may have indicated an away hand-movement, and the color blue a toward hand-movement (de Vega, Moreno, & Castillo, 2013; de Vega & Urrutia, 2011). In Kaschak and Borreggine (2008), instead of a color change, the letter “P” or “Q” occurred to indicate which button the participants were to press once the letter appeared. In the experiments with a motion-cue, the transfer verb of the sentence “jumped” toward or away from the participant. This movement was the cue for the participant to immediately press the near or the far button according to the perceived movement (de Vega et al., 2013; de Vega & Urrutia, 2011). In these experiments with more perceptual cues, participants were explicitly told to read the stimulus materials. To ensure that participants were trying to understand the sentences, different kinds of tasks were added. For instance, a memory test, a sentence completion task, or a word probe task was administered.

1.2.2 Linguistic material.

The included studies also differed with regard to the applied linguistic material. Even though the ACE was also examined on the word level, we decided to only include studies where the linguistic material consisted of sentences, as in the original ACE experiment. All our included studies involved transfer sentences, denoting a transfer from one person to another (“Courtney handed you the notebook”; “You handed Courtney the notebook”). Glenberg and Kaschak (2002), Lugli et al. (2012) as well as Papesh (2015, experiment 6,7,8) additionally used imperative sentences as a second

sentence type (“Open the drawer”; “Close the drawer”). We excluded the study by Kaup et al. (2012) because instead of transfer sentences, they only used sentences with state descriptions (“The drawer is open/shut”).

Most of the included studies applied sentences with the pronoun “You” (“You gave a pizza to Louis”). Some studies investigated the influence of perspective by adding sentences with a third-person perspective using names (“Lea gave a pizza to Louis”) or the pronouns He/ She (“He received the letter”) (Gianelli et al., 2011; Schwarzkopf et al., 2011; van Dam & Desai, 2017). Finally, some studies only used sentences with a third person perspective Bergen and Wheeler (2010, 2005).

In all included studies, the stimulus material consisted of written or spoken sentences which included the movement-direction “toward or away from the body”. In most studies, the sentences were visually presented on the computer screen with the participant reading the sentence at one go or segment by segment (de Vega et al., 2013; Schwarzkopf et al., 2011). In some studies, researchers presented either the full sentences auditory or presented the sentence for the most part auditory, except for the transfer verb, which was displayed visually on the screen (Borreggine & Kaschak, 2006; de Vega & Urrutia, 2011; Kaschak & Borreggine, 2008). Some experiments used the exact same or a part of the original linguistic material from Glenberg and Kaschak (2002) these are Kaschak and Borreggine (2008), Papesh (2015, experiment 6,7,8) and Vinson et al. (2017). Others translated the original materials to investigate the ACE in different languages (Gianelli et al., 2011) or created new linguistic materials in other languages. Included languages in the meta-analysis are English (Bergen & Wheeler, 2005, 2010; Borreggine & Kaschak, 2006; De Scalzi et al., 2015; Gould & Michaelis, 2018; Kaschak & Borreggine, 2008; Papesh, 2015; van Dam & Desai, 2017; Vinson et al., 2017), German (Diefenbach et al., 2013; Schwarzkopf et al., 2011), Spanish (de Vega et al., 2013; de Vega & Urrutia, 2011), Italian (Glenberg, Sato, Cattaneo, Riggio, et al., 2008; Lugli et al., 2012) and French (Gianelli et al., 2011).

We excluded experiments from the meta-analysis in which sentences in sign-language were used. Sign language has its discrete grammar and uses facial expressions, gestures,

and body posture to convey linguistic information. The standardized signs comprise four phonological aspects - those are hand form, hand direction, place of execution, and movement. In Sign language, the visual modality is used for communication and offers a high degree of iconicity (Vinson et al., 2017). In ACE experiments using Sign language, deaf participant performed a standard ACE-experiment, but instead of written or spoken sentences, they viewed videos in which a person signed the sentences. As movements in sign language are used to convey meaning, there is a conflict between the semantic direction of the sentence and the perceived direction for certain sentences used for ACE-examining. For example, to sign the sentence “You open the drawer”, the person in the video executes a movement toward his/ her own body. This means that for the participant the perceived direction is away but the semantic direction is toward (Secora & Emmorey, 2015). Secora and Emmorey (2015) investigated the ACE using sign language and found that the ACE occurs considering the semantic direction of the sentence, not impaired by the perceptual direction of the sign, like it would be expected in an ACE-experiment with written or spoken language. In contrast, Vinson et al. (2017) found that the ACE was not present in sign language and suggested that this is because of the higher iconicity of signed sentences compared to written or spoken sentences. Vinson et al. (2017) claimed that because of the higher iconicity less mental simulation is needed for language comprehension in sign language (for further discussion see McCullough, Saygin, Korpics, & Emmorey, 2012; Secora & Emmorey, 2015; Vinson et al., 2017). Because of this disagreement in the literature regarding sign language in ACE research, and the circumstance that in all other studies the linguistic material was provided in a written or auditory format, not as a video (as in all studies with sign language) we decided to exclude ACE experiments using sign language.

The original study (Glenberg & Kaschak, 2002) as well as a considerable number of studies in this meta-analysis (Bergen & Wheeler, 2005; Borreggine & Kaschak, 2006; Diefenbach et al., 2013; Gianelli et al., 2011; Glenberg, Sato, Cattaneo, Riggio, et al., 2008; Kaschak & Borreggine, 2008; Papesh, 2015; Schwarzkopf et al., 2011; van Dam & Desai, 2017; Vinson et al., 2017) included sentences expressing a transfer of concrete

objects (“Katie handed the puppy to you”) and also sentences describing an abstract transfer (“Andy pitched you the idea”). The question whether the ACE can be observed for abstract transfer is particularly interesting because the comprehension of abstract language seems to challenge the embodiment view. As mentioned above, the framework of embodiment hypothesizes that a person can comprehend language through the mental simulation of sensorimotor experiences, which were generated during interaction with the physical world. But abstract language, like the sentence “Andy pitched you the idea”, does not allow to fall back on directly experienced movements towards or away from the body. The challenge to explain the comprehension of abstract language within the embodied cognition framework has often been identified as being crucial for the plausibility of the framework of embodiment. Zwaan (2014) suggested that comprehenders rely on symbolic representations (e.g., frame-semantic meanings of lexical items) during semantic composition, although these symbolic representations may ultimately activate grounded representations. Other authors assume that abstract information is mapped onto experienced domains like the domain of valence or space (Kaup, De la Vega, Strozyk, & Dudschig, 2016). For further discussion on abstract language in the framework of embodiment, see Kaup et al. (2016) as well as Pecher, Boot, and Van Dantzig (2011). Another explanation, why the ACE could be observed in abstract sentences is provided by studies which examine the “semantics of syntax” (van Dam & Desai, 2016). The basic idea of this research field is that syntactic constructions convey meaning on their own and evoke sensory-motor activation themselves. The explanation is that children early on learn syntactic constructions for example, for transfer-sentences like “Give Dada the cup”. Transfer-sentences denote a transfer of an object from oneself to another person. These early learned syntactic constructions become highly correlated with the movement-direction “toward or away from the body”. Because the syntactic structure is associated with the movement toward-away from the body the ACE could occur independently from whether the content of the sentence is concrete or abstract (De Scalzi et al., 2015; Glenberg & Gallese, 2012; van Dam & Desai, 2016). Because the original study involved both

abstract and concrete transfer sentences, we decided to include studies independent of whether the sentences involved concrete or abstract transfer.

Some researchers looked at additional grammatical and linguistic factors, which could potentially influence motor simulation processes and, therefore, the magnitude of the ACE (e.g., Gould & Michaelis, 2018: “Lisa gave Pongo the treat“ vs. “Lisa gave the treat to Pongo“; Bergen & Wheeler, 2010: “John is closing the drawer“ vs. “John has closed the drawer.“).

1.2.3 Response movements.

The studies included in our meta-analysis differed with respect to the type of response movements participants made when processing the sentences. The response action in all included studies required an actual finger or a hand movement toward or away from the body. As in the original ACE-experiment, the most used response apparatus was a button-box or a modified keyboard. Participants were asked to press and hold a middle button to start the trial, and for responding release the middle button, move toward or away from the body and press the far or the near button. But there were further response devices in our study set, namely joystick (Gianelli et al., 2011) and mouse (Lugli et al., 2012; Papesh, 2015).

1.2.4 Dependent Variable.

In their original study, Glenberg and Kaschak (2002) used the reading time as their dependent variable. Reading time is defined as the time between sentence onset and release of the middle button. Sometimes this time is also referred to as the lift-off time. As a further dependent measure, many studies recorded the time it took participants from releasing the middle button to pressing the response button, often referred to as the movement time. Yet other studies measured a combination of these dependent variables. For example, Diefenbach et al. (2013) measured the total response time, namely the time between sentence onset and the pressing of the response button. Some studies additionally analyzed the proportion of accurate judgments as dependent variable. As in most of these studies, no ACE was observed in the accuracy data, we decided to not include accuracy data in our meta-analysis but instead focus on response times as

dependent variables.

1.2.5 Time point of responding during sentence processing.

Some included studies explored how different time points of the response action influence the occurrence of the ACE. Therefore, the researchers integrated a response cue to examine the effect of time – as for example Borreggine and Kaschak (2006). Like in all other experiments, their response-apparatus had a near button (labeled as “P”) a far button (labeled as “Q”) and a middle button that participants held down to initiate sentence presentation. At some point during each trial, the letter P or the letter Q appeared on the screen, indicating which button the participants were to press if they wanted to make a yes-response (the sentence is sensible). Participants should refrain from responding when the sentence was nonsensical. The time point at which the letter appeared was manipulated. The cue occurred immediately after the beginning of sentence presentation or with a delay of 50, 500, or 1000 ms after the offset of the sentence. Interestingly, the time point at which the response action occurs during sentence processing does seem to have an influence on whether the ACE occurs as a *facilitation effect* (faster reaction time in a compatible trial compared to an incompatible trial) or as an *interference effect* (faster reaction time in an incompatible trial compared to a compatible trial). For example, the results of the study by de Vega et al. (2013), revealed an ACE as an interference effect when the cue was presented with a short delay but when the cue was presented with a long delay, the ACE occurred as a facilitation effect. In the study from Borreggine and Kaschak (2006), there was an ACE facilitation effect when the cue was presented immediately after the onset of the sentence, whereas this effect was reversed when the cue was presented with a long delay after the offset of the sentence. Because the existing evidence strongly suggests that the time point at which the response is executed has an impact on whether the ACE occurs with a positive or with a negative effect direction, we decided to include *Delay* as a factor in our meta-analysis.

1.3 Aim of the meta-analysis

As the previous section has stated, the ACE is an extremely influential action compatibility effect in the framework of embodied cognition. It has been replicated and extended in a comprehensive series of experiments and is one of the most widely cited evidence for embodied cognition. But lately, there have been difficulties to reliably observe the ACE. Some current replication attempts showed no hint of an ACE. For example, Papesh (2015) attempted to replicate the ACE in 9 experiments, but 8 of them resulted in replication failures. These repeated failures to observe the ACE, motivated Papesh (2015) to review the existing literature and to re-evaluate whether the existing literature is truly convincing. To examine the ACE literature more closely, Papesh (2015) calculated scaled JZS-Bayes factor values and discovered that the empirical data for the ACE is poor in most cases. Only a few studies actually provided strong evidence for an ACE and many studies did in fact support the null hypothesis (no ACE), although they are typically treated as positive evidence in the literature. As a result, researchers in the field of embodied cognition have come to agree that it is becoming increasingly urgent and important to know whether the ACE is indeed a reliable effect or whether it may rather reflect bias in reporting. Thus, the main goal of the present meta-analysis is to compile previously published ACE studies with a study design similar to the original one (Glenberg & Kaschak, 2002) in order to estimate the size of the ACE and to investigate whether it is significantly different from zero. Furthermore, the extent of selective reporting in the ACE literature will be estimated using various methods. If a publication bias is present, it will be included in the estimation of the effect size of the ACE, ultimately bringing us closer to a conclusion whether the ACE is a reliable effect or whether it rather reflects a bias in reporting. Because of the striking fact that the ACE seems to appear with positive and negative effect direction we included *Delay* in the meta-analysis to check if it is decisive for effect direction of the ACE appearance.

2 Method

2.1 Sample of studies

We aimed at selecting studies that investigated the ACE in a paradigm similar to the one used in the original study by Glenberg and Kaschak (2002). We assumed that manuscripts reporting these studies would always cite the original paper. Using the electronic database “Web of Science“, we clicked on the “Times Cited“-button to let us itemize all articles that cite the publication of Glenberg and Kaschak (2002). This resulted in 1013 articles (Web of Science; February 26, 2019). Furthermore, we used the reference sections of current articles to find out whether we had missed some relevant articles.

We scanned all discovered articles and included only studies published in English, conducted in the first language of the participants and with healthy adults as participants. The study by De Scalzi et al. (2015) involved a group of people with Alzheimer’s disease. From this study we only included data from the healthy control groups. Further, we only selected studies that reported response time and statistics that allowed us to accurately calculate the effect size. Since the original study by Glenberg and Kaschak (2002) was conducted with sentences as materials, one inclusion criterion was that the stimulus material had to consist of sentences that explicitly denote a toward or away movement. Studies were excluded when the stimulus material consisted of words, for example, valenced words (Freina, Baroni, Borghi, & Nicoletti, 2009; Wang et al., 2018), or words denoting objects that are typically handled with a movement towards or away from the body (Van Dam, Rueschemeyer, Lindemann, & Bekkering, 2010; van Dam, Brazil, Bekkering, & Rueschemeyer, 2014) or when sentences were used which do not clearly describe a toward or away movement (e.g., state description (Kaup, Lüdtke, & Maienborn, 2010)). We also ruled out studies that presented whole texts as stimulus material (e.g., a text describing a protagonist making metaphorical forward movements (Horchak, Giger, & Pochwatko, 2014)). Additionally, we only added a study when the response-action required an actual toward or away arm-movement. We therefore excluded Liu and Bergen (2016) as well as experiment 2B from Glenberg

and Kaschak (2002), because in both studies there was no actual toward-away arm movement required for responding. Throughout the experiment, the participants in these experiments held one finger over the “yes“ and the other finger over the “no“ button, instead of moving the finger to the response-buttons. As already mentioned 1.2.2, we also excluded experiments that used videos with signed language sentences as stimulus material or a priming procedure (movement prior to sentence presentation onset). Finally, we decided not to incorporate experiments that included a unique manipulation that could have affected the ACE in a complex way. For this reason, we excluded Experiment 1, 2 and 5 from Papesh (2015), because a “disembodied“ sense of self was added to the experiment, and Experiment 3 from Gianelli et al. (2011), because names were displayed on the right and the left side of the computer screen, so the sentences-direction could be interpreted as movement from left to right/ right to left. Regarding the study from Diefenbach et al. (2013), we only included the data from the regular group. The inverted group had an inverted spatial relationship between actions and effects such that a response movement to the near button resulted in an action effect located away from the body. The supplementary materials contain an overview of all the studies selected for the meta-analysis as well as the statistics with which we have calculated the respective effect size (Table 2).

As mentioned in the previous section (1.2.5) it could be hypothesized that the time point at which the response is executed has an impact on whether the ACE occurs with a positive or with a negative effect direction. Therefore, we decided to include *Delay* as a factor in our meta-analysis. For investigating the influence of *Delay* we divided the studies into two subgroups, *no delay* and *with delay*. Studies were assigned to the *with delay* subgroup when the response cue was presented with a delay after offset of the critical word (Borreggine & Kaschak, 2006; de Vega et al., 2013; de Vega & Urrutia, 2011). Studies that varied the timing during sentence presentation, such that cue presentation was before the offset of the critical word, were assigned to the subgroup *no delay* (Diefenbach et al., 2013; Kaschak & Borreggine, 2008).

2.2 Effect size analysis

For all calculations performed in the meta-analysis as well as for the effect size calculations, we used the Comprehensive Meta-Analysis (CMA, Version 3.3.070, 2014) software. We estimated the effect sizes for each study from the reaction times (RT) of the behavioral data. The majority of studies only reported an analysis with participants as random factor ($F1$), but in a few studies, an additional analysis was reported which treated items as random factor ($F2$). We always calculated the effect size from the exact overall $F1$ -values. In some studies, the ACE was reported for two or more dependent variables. Since the ACE has typically been observed on the reading time measure, and Glenberg and Kaschak (2002) used the reading time as dependent variable in their original study. If there were multiple dependent variables the reading time, was chosen as the dependent measure for calculating the effect size. Effect size was calculated from reading time in de Vega et al. (2013), de Vega and Urrutia (2011, experiment 2), Gianelli et al. (2011), Lugli et al. (2012), Schwarzkopf et al. (2011), van Dam and Desai (2017), Vinson et al. (2017) and Papesh (2015). Dependent variables were based on the movement time in Bergen and Wheeler (2005), Bergen and Wheeler (2010), Borreggine and Kaschak (2006), de Vega and Urrutia (2011, experiment 1) Glenberg, Sato, Cattaneo, Riggio, et al. (2008), Gould and Michaelis (2018) and Kaschak and Borreggine (2008), based on total response time in (Diefenbach et al., 2013) and based on Latency data in (De Scalzi et al., 2015).

For each study, the effect size was calculated as Cohen's d . This is the standardized mean difference - here, the difference between the compatible condition (sentence direction and response direction match) and the incompatible condition (sentence direction and response direction mismatch). A positive effect size indicates a positive ACE. RT in this case was shorter for the compatible trials than for the incompatible trials (ACE as facilitation effect). A negative effect, however, indicates that the RT was faster for the incompatible trials than for the compatible trials (ACE as interference effect). Compatibility was manipulated within participants in most of the studies. In these cases, Cohen's d was calculated from the respective t -value and the sample size.

In cases where compatibility was manipulated between participants, Cohen's d was calculated from the t -value and the sample sizes of the two groups. Many studies reported only an F -value. In these cases, we calculated the t -value by the formula $t = \sqrt{F}$. In Gould and Michaelis (2018), only a Chi-square value was reported, which we treated as an F -value and calculated the t -value in the same way as in the other studies. De Scalzi et al. (2015) reported data from two independent subgroups - young adults and older adults (the subgroup with Alzheimer's disease was excluded). Since these subgroups were independent of each other, we treated them as separate studies (Borenstein, Hedges, Higgins, & Rothstein, 2009, p. 115).

One aim of our meta-analysis was to calculate the overall weighted mean effect size. In principle, there are two statistical models for doing this, the fixed-effect model and the random-effects model. Under a fixed-effect model it is assumed, that there is one common (true) effect size that is exactly the same in all included studies, and that all differences in the observed effects are due to sampling error. Opposing this, we have chosen the random-effects model which is based on the assumption that the true effect size may differ from one included study to the next and that the true effect sizes are distributed around some common mean (Borenstein et al., 2009). The random-effects model was applied because the included studies vary considerably, for example, in the task, the language of the stimulus material, and the dependent measure. These different characteristics of the included studies make it reasonable to assume that the studies are based on different true effect sizes and that the random-effects model is, therefore, the appropriate choice.

To further look at the variance between the single results the heterogeneity of the effect size was quantified. With the Q -statistic (a measure of weighted quadratic deviations) as a measure of heterogeneity, we tested whether all studies share one common true effect size or whether the true effect size differs between the studies. Furthermore, I^2 will be reported, indicating what proportion of the observed variance is due to real differences in effect size. An I^2 close to zero tells us that nearly all of the observed variance is due to a random error. On the opposite, a large I^2 tells us that the true

effects vary across studies. The latter case suggests to search for reasons to explain this variance, for example by a subgroup analysis. We therefore decided to check the heterogeneity first before conducting our subgroup analysis for the factor *Delay*. To assess the potential impact of publication bias the *funnel plot* and Duval and Tweedie's (2000) *Trim and Fill procedure* were applied. Q , I^2 , the funnel plot and the Trim and Fill procedure are implemented in CMA and will be reported for each analysis.

2.3 Fisher's method

Data were analyzed by using Fisher's method (Fisher, 1934) as a second meta-analytic approach. Using Fisher's method p -values were combined by using the formula:

$$\chi^2 = -2 \sum_{i=1}^k \ln(p_i). \quad (1)$$

Where k is the number of independent studies and p_i denotes the p -value of the i_{th} study. χ^2 follows a chi-square distribution with $2k$ degrees of freedom. The p -values of each study are shown in Table 2. As with the effect size analysis, we first performed the analysis for all p -values, then analyses were performed separately for the *no delay* and *with delay* subgroup. If the effect direction of an individual study was in the other direction than expected, we took the logarithm from $1 - p_i$. For example, for the *no delay* condition the expected effect direction of the ACE is positive, but in Papesh (2015, experiment 3) effect direction is negative with $p = .82$, we arrived at $\ln(1 - .82)$. For the *with delay* condition it was vice versa because the expected effect direction of the ACE is negative. For Borreggine and Kaschak (2006, experiment 2) effect direction is positive with $.604$, we arrived at $\ln(1 - .604)$.

3 Results

3.1 Effect size analysis

Figure 1 shows the effect sizes of the 30 selected studies as well as the determined overall weighted mean effect size for the investigated ACE. The overall effect size is positive and significantly different from zero ($d = .129$, 95% CI = .035 to .223, $p = .007$). The significant Q -Statistic ($Q(29) = 79.811$, $p < .001$) leads us to rejecting the null hypothesis that all studies share a common effect size. Instead, there is true heterogeneity between the ACE-studies which means that the effect-sizes between the studies vary. 63.664% of the observed variance reflects real differences in effect sizes ($I^2 = 63.664$). Since I^2 indicates substantial heterogeneity (Deeks, Higgins, & Altman, 2008), the choice to perform a separate analysis for the two conditions *no delay* and *with delay* is clearly supported by the data (Borenstein et al., 2009). The publication bias was investigated by using a funnel plot. This funnel plot (Figure 2) indicates a publication bias. Using the Trim and Fill procedure as a method for assessing publication bias, it is suggested that three studies should be trimmed and filled. The estimate of the adjusted mean effect size after application of Duval and Tweedie's Trim and Fill is smaller than the observed mean effect size but is still significantly different from zero ($d = .097$, 95% CI = .002 to .192).¹ See Table 1 for an overview of observed and adjusted effect sizes.

¹ The impression of an asymmetric funnel plot and presence of publication is confirmed by further methods. Kendall's tau = .223, $p(\text{one-tailed}) = .042$ (Begg & Mazumdar, 1994); Egger's regression intercept = 1.448 with $t(28) = 1.537$, $p(\text{one-tailed}) = .068$ (Egger, Smith, Schneider, & Minder, 1997)

Figure 1. Forest plot for the overall ACE (E = Experiment).

Figure 2. Funnel plot for the overall ACE. Blank circles represent the observed effect sizes, filled circles illustrate trimmed and filled studies.

Table 1

Summary of the observed and adjusted mean effect sizes (Cohen's d)

	Observed mean effect size (d)	Observed 95% CI	Adjusted mean effect size (d)	Adjusted 95% CI
overall	.129	.035 to .223	.097	.002 to .192
no delay	.208	.112 to .304	.176	.079 to .273
with delay	-.138	-.258 to -.019	-.138	-.258 to -.019

Looking at the subgroups, the separate analysis of the weighted mean effect size for the condition *no delay* with 24 underlying effect sizes (Figure 3) indicated an effect size that is positive and significantly different from zero ($d = .208$, 95% CI = .112 to .304, $p < .001$). The significant Q -Statistic ($Q(23) = 48.230$, $p = .002$) provides evidence that the true effects of the included studies vary. 52.312% of the observed variance is due to real differences in effect sizes ($I^2 = 52.312$). Referring to the funnel plot (Figure 4), there is evidence of publication bias. It is recommended to trim and fill 3 studies, resulting in an adjusted mean effect size of $d = .176$ (95% CI = .079 to .273) after applying Duval and Tweedie's Trim and Fill.

The analysis of the weighted mean effect size for the subgroup *with delay* with 6 underlying effect sizes (Figure 5) also indicated an effect size that is significantly different from zero, but this time being negative ($d = -.138$, 95% CI = $-.258$ to $-.019$, $p = .023$). The Q -Statistic did not reach significance ($Q(5) = 6.127$, $p = 0.294$). However, this lack of significance may be caused by low power due to the small number of studies ($n = 6$) in this subgroup (Borenstein et al., 2009). The proportion of the observed variance which reflects real differences is 18.389% ($I^2 = 18.389$). The funnel plot (Figure 6) indicates that there is no publication bias, and no study needs to be trimmed and filled, see Table 1.

The weighted mean effect size of the condition *no delay* is significantly positive and the weighted mean effect size of the condition *with delay* is significantly negative. This indicates that there is a difference between these two conditions, which is supported by

Figure 3. Forest plot for the subgroup no delay (E = Experiment).

Figure 4. Funnel plot for the subgroup no delay. Blank circles represent the observed effect sizes, filled circles illustrate trimmed and filled studies.

Figure 5. Forest plot for the subgroup with delay (E = Experiment).

Figure 6. Funnel plot for the subgroup with delay. The circles represent the observed effect sizes. When using the random effects model to search for missing studies, no studies are trimmed and filled.

a significant result of the Q -statistic ($Q(1) = 19,582, p < .001$).² We conclude that the effect size for the ACE is significantly different depending on whether the ACE is investigated in a study with delay or without delay.

² Tau-squared is not considered to be equal for the two subgroups. Tau-squared was separately estimated for each subgroup and not pooled across subgroups.

3.2 Fisher's method

As with the effect size analysis, we initially considered all studies together. See Figure 7 for the CDF for all p -values. Note that under the H_0 , p -values would follow a uniform distribution. This means if there is no ACE and no publication bias, there would be a uniform distribution of p -values with a mean of $p = .5$ ($se = .053$).

Regarding all studies ($n = 30$) Fisher's method suggested to reject the null hypothesis according to which there is no ACE ($\chi^2(60) = 124.379$, $p < .001$). This was confirmed in the separate analysis for the *no delay* condition where a positive effect direction was expected ($\chi^2(48) = 119.286$, $p < .001$) as well as for the *with delay* condition where a negative effect direction was expected ($\chi^2(12) = 21.599$, $p = 0.042$). In other words, Fisher's method provides evidence for an ACE as facilitation effect (*no delay* condition) and as interference effect (*with delay* condition).

Figure 7. Estimated CDF for all p -values. Red line denotes $p = .05$

4 Discussion

The effect size analyses revealed an overall effect size for the ACE which was significantly different from zero ($d = .129$). A significant positive effect size was found for the ACE in the subgroup *no delay*. For the subgroup *with delay*, the effect size was significantly negative, establishing the ACE as an interference effect. We conclude that the factor *Delay* is a parameter of interest in whether the ACE appears as a facilitation or interference effect. This factor should thus clearly receive attention in further research. The results of the second meta-analytic approach (Fisher's method) point in the same direction and provide evidence for the existence of an ACE effect and the influence of the factor *Delay* on the effect direction of the ACE.

Furthermore, in the first meta-analytic approach (3.1 Effect size analysis) it was revealed that there is a publication bias in the ACE literature. After correction for publication bias, the adjusted effect size for the ACE was even smaller, but still significant. To our knowledge, there is no opportunity in the second meta-analytic approach (3.2 Fisher's method) to answer the questions whether there is evidence of bias in the ACE literature or how much of an impact the bias might have.

But the first meta-analytic approach, where the funnel plot and Duval and Tweedie's Trim and Fill procedure were used for bias correction, also has weaknesses. The Trim and Fill procedure performs poorly when there is considerable heterogeneity between studies. Since this was the case in this meta-analysis, the estimated effect of the publication bias and the adjusted mean effect size of the ACE should be treated with caution (Peters, Sutton, Jones, Abrams, & Rushton, 2007; Terrin, Schmid, Lau, & Olkin, 2003). Furthermore, as Simonsohn, Nelson, and Simmons (2014a, 2014b) criticizes, the employed Trim and Fill procedure assumes that publication bias reflects the suppression of small effects (regardless of their significance). However, it is assumed that the publication bias in psychology is mainly due to the suppression of non-significant results (Rosenthal, 1979). Studies are submitted and published depending on whether they are significant or not, regardless of the effect size. As shown by Simonsohn et al. (2014b), the Trim and Fill method is inadequate when the

publication bias is mainly caused by suppression of non-significant results.

To further assess for distorting research practices, we skimmed through the papers included in our meta-analysis. The impression is that behaviors that could be termed p-hacking (Simonsohn et al., 2014a) cannot be ruled out. In addition, there is further evidence of publication bias in the ACE literature. Information is provided by researchers who participated in the Multi-lab study (Morey et al., in press). To quote from the article: “Several of the researchers involved in the current replication effort know about unpublished failures to replicate the ACE from other labs, or have unpublished studies in which they failed to produce the effect themselves” (Morey et al., in press, p. 5).

Thus, there is evidence of bias in the ACE literature, and we can assume that these biasing research practices had skewed our understanding of the ACE as a powerful effect (this is in line with Papesh (2015)). Both non-significant studies in the file drawers of ACE researchers as well as distorting behaviors, such as only reporting the significant analyses, fake the impression that the ACE is a powerful effect. The treatment of the ACE as a benchmark phenomenon in favor of the embodied account of language comprehension should be reconsidered and more care should be taken when using the ACE paradigm to investigate the embodied model of language comprehension (Morey et al., in press; Papesh, 2015).

So what can be concluded from the failed attempts in the literature to replicate the ACE, as a key empirical finding in the embodiment framework? Failure in replication can have multiple causes. Recent research stresses the importance of the “base rate“. The replication rate is strongly affected by the base rate of true effects within a research area. If the base rate is low in a particular research field, then the proportion of false positives will be high and therefore the replication rate will be low. Ulrich and Miller (2020) as well as Wilson and Wixted (2018) argued that a low base rate of true effects is the most important factor for low replicability. We consider it likely that Embodiment might be a research field that has a low base rate of true effects. Therefore, it is not surprising that certain effects are hard to replicate.

The question arises what conclusions can be drawn about the embodiment framework, given that the ACE has been cited very often in literature as an example and evidence for the interaction between cognitive processes and motor processes. It would be hasty to conclude that the failure to replicate the ACE as a key empirical support weakens the whole embodiment framework (Morey et al., in press).

A decisive argument for not disapproving the whole embodiment framework is that it receives support from paradigms focusing on other meaning dimensions, such as the direction of turning movements (e.g., Zwaan and Taylor (2006)) or the amount of manual experience a person has with an object (Yee, Chrysikou, Hoffman, & Thompson-Schill, 2013). In addition, there is evidence for embodiment with respect to the shape or orientation of objects (Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2002), their typical location in vertical space (e.g., Dudschig and Kaup (2017); Günther et al. (2020); Thornton, Loetscher, Yates, and Nicholls (2013)), or their typical color (Connell & Lynott, 2009). Also, there is evidence from other domains than language comprehension, as working memory (Shebani & Pulvermüller, 2013) or number processing (Fischer, 2012). Further empirical evidence is provided by studies looking at neuropsychological measures (e.g., González et al. (2006); Hauk et al. (2004)).

Furthermore, the statements of the meta-analysis are limited to the classical ACE paradigm. They should not be extended to other compatibility effects in the domain of embodiment. The classical ACE, which was applied in all included studies in the meta-analysis, differs from other compatibility paradigms and the replication problems might be due to some specific features of the classical ACE. One specific feature of the classical ACE is that the toward-away dimension is mainly expressed through the sentence level. Conclusions about the direction can hardly be based on single words. For example, in Borreggine and Kaschak (2006) the sentence “Mike rolled you the marble” expressed a toward sentence, and “You rolled Mike the marble” expressed an away sentence. The only difference between these two sentences is the order of the words. None of the words implies the direction of the movement solely. To our knowledge there are only a few studies, considering the toward-away dimension, which

are working on word level. For example, Van Dam et al. (2010, 2014) employed words denoting objects for which functional use is related to a movement either toward (body words, e.g., “spoon“, “ring“, “wine glass“) or away (world words, e.g., “computer“, “umbrella“, “light bulb“) from the body. But most of the ACE studies express the toward-away dimension through the sentence level. But other motor-compatibility paradigms which are based on different meaning dimensions can be expressed lexically by means of a single word (e.g., location in vertical space). The conclusions that can be drawn from this meta-analysis are thus reduced to the classic action-compatibility effect which reflects comprehension processes at the sentence level.

5 Conclusion

Both meta-analytic methods indicated that the action-sentence compatibility effect is an existing but very small effect. Additionally, both methods revealed an influence of delay in this compatibility paradigm. In these studies, where participants could respond immediately after sentence offset, ACE showed an overall positive effect. Whereas the overall meta-analytic effect direction was negative when participants had to respond to a delayed response cue. Another finding is that there is some evidence of bias in the ACE literature. This bias may have exaggerated the significance of the ACE as an effect with high power and overemphasized its status as a prime example for the embodied account of language comprehension.

6 References

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Supplementary material

Table 2

Overview of all incorporated studies

Authors	Title	Exp Nr.	Language	Response mode	Congruence	Design	N	Reported statistics	P-value	T-value & Effect direction	Delay	Explanatory notes
Gould & Michaelis, 2018	Match, mismatch, and envisioning transfer events: How verbal constructional bias and lexical-class concord shape motor simulation effects	1	english	Button press	Away sentence – away arm movement	between	40	$\chi^2(1, n=40) = 2.88$	$p = .09$	t = 1.697 (congruent: n=20; incongruent: n=20) Effect direction: positive	No delay	All sentences were away-sentences. We treated the chi-square value as an F-value and calculated the t-value as in the other studies. ($t = \sqrt{2.88}$)
van Dam & Desai, 2017	Embodied Simulations Are Modulated by Sentential Perspective	A	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	27	$t(26) = .08$	$p = .94$	t = .080 Effect direction: positive	No delay	We thank Rutvik Desai for letting us know the result of the overall congruency effect of the separate ANOVA for Experiment A.
Vinson, Perniss, Fox, & Vigliocco, 2017	Comprehending sentences with the body: Action compatibility in British Sign Language?	4	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	16	$F(1, 15) = 8.13$	$p = .012$	t = 2.851 Effect direction: positive	No delay	Deaf participants
Papesh, 2015	Just Out of Reach: On the Reliability of the Action-Sentence Compatibility Effect	3	english	Mouse	Away sentence – away arm movement; Toward sentence- toward arm movement	within	37	Reading time: $F(1, 35) = .05$	$p = .82$	t = .224 Effect direction: negative	No delay	

			4A	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	52	Reading time: $F(1, 50) = .01$	$p = .92$	$t = .100$ Effect direction: positive	No delay
			4B	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	22	Reading time: $F(1, 21) = .88$	$p = .36$	$t = .938$ Effect direction: negative	No delay
			6	english	Mouse	Away sentence – away arm movement; Toward sentence- toward arm movement	within	91	Reading time: $F(1, 90) = .01$	$p = .91$	$t = .100$ Effect direction: positive	No delay
			7	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	59	Reading time: $F(1, 58) = 3.68$	$p = .06$	$t = 1.918$ Effect direction: positive	No delay
			8	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	86	Reading time: $F(1, 85) = .14$	$p = .71$	$t = .374$ Effect direction: negative	No delay
De Scalzi, Rusted, & Oakhill, 2015	Embodiment Effects and Language Comprehension in Alzheimer's Disease	1 young adults	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	35	$F(1, 34) = 4.62$	$p = .039$	$t = 2.149$ Effect direction: positive	No delay	The Alzheimer-group was excluded. The subgroups <i>young adults</i> and <i>older adults</i> are independent of each other, so we can treat each as if it were a separate study (Borenstein, Hedges, Higgins, & Rothstein, 2009, p. 115).
		1 older adults	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	20	$F(1, 19) = 4.75$	$p = .042$	$t = 2.179$ Effect direction: positive	No delay	

Diefenbach, Rieger, Massen, & Prinz, 2013	Action-sentence compatibility: the role of action effects and timing	1	german	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	8	Regular group: $F(1, 7) = .56$	$p = .48$	$t = .748$	No delay	Because we did not want to incorporate unique manipulations that could have affected the ACE in a complex way, we only included the data from the regular group in the meta-analysis. We thank Christiane Diefenbach for providing us with the raw data of the experiment, so we could calculate the ACE for the regular group only.
										Effect direction: negative		
		2	german	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	20	Regular group: $F(1, 19) = .07$	$p = .794$	$t = .265$	No delay	Because we did not want to incorporate unique manipulations that could have affected the ACE in a complex way, we only included the data from the regular group in the meta-analysis. We thank Christiane Diefenbach for providing us with the raw data of the experiment, so we could calculate the ACE for the regular group only.
										Effect direction: positive		
de Vega, Moreno, & Castillo, 2013	The comprehension of action-related sentences may cause interference rather than facilitation on matching actions	1	spanish	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement						With delay	Experiment 1 cannot be incorporated in the meta-analysis since the exact F-value of the Transfer direction x Movement direction interaction is not reported.
		2								$t = 2.345$		
			spanish	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	40	$F(1, 39) = 5.50$	$p = .024$	Effect direction: negative	With delay	

Lugli, Baroni, Gianelli, Borghi, & Nicoletti, 2012	Self, others, objects: How this triadic interaction modulates our behavior	1	italian	Mouse	Away sentence – away arm movement; Toward sentence- toward arm movement	within	22	$F(1, 21) = 6.166$	$p = .022$	$t = 2.484$ Effect direction: positive	No delay	
		2	italian	Mouse	Away sentence – away arm movement; Toward sentence- toward arm movement	within	22	$F(1, 21) = 8.453$	$p = .008$	$t = 2.907$ Effect direction: positive	No delay	We thank Luisa Lugli and Anna Borghi for letting us know the result of the ANOVA with Movement (near-far), Target (oneself-block2, generic-block2) and Valence (positive, negative) as within-subject factors.
Gianelli, Farnè, Salemme, Jeannerod, & Roy, 2011	The Agent is Right: When Motor Embodied Cognition is Space-Dependent	1	french	Joystick	Away sentence – away arm movement; Toward sentence- toward arm movement	within	32	$F(1, 31) = 4.52$	$p = .042$	$t = 2.126$ Effect direction: positive	No delay	
		2	french	Joystick	Away sentence – away arm movement; Toward sentence- toward arm movement	within	34	$F(1, 33) = 3.043$	$p = .09$	$t = 1.744$ Effect direction: negative	No delay	
de Vega & Urrutia, 2011	Counterfactual sentences activate embodied meaning: An action-sentence compatibility effect study	1	spanish	Button press	Away sentence – away “arm movement”; Toward sentence- toward “arm movement”	within	89	$F(1, 87) = .132$	$p = .717$	$t = .363$ Effect direction: negative	With delay	We thank Manuel de Vega for letting us know the exact F-value of the overall releasing time for the interaction of Sentence Direction x Response Direction.
		2	spanish	Button press	Away sentence – away “arm movement”; Toward sentence- toward “arm movement”	within	69	$F(1, 68) = 4.586$	$p = .036$	$t = 2.141$ Effect direction: negative	With delay	
Schwarzkopf, Weldle, Müller, & Konieczny, 2011	Mental simulation of spatial perspective during sentence comprehension	1	german	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	24				No delay	Since the exact F-value of the main effect for compatibility is not reported, this study cannot be incorporated into the meta-analysis
Bergen & Wheeler, 2010	Grammatical aspect and mental simulation	1	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	70	$F(1, 69) = 9.82$	$p = .003$	$t = 3.134$ Effect direction: positive	No delay	

		2	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement						No delay	Since the exact F-value of the Sentence Direction x Response Direction interaction is not reported, the study cannot be incorporated into the meta- analysis.
Kaschak & Borreggine, 2008	Temporal Dynamics of the Action – Sentence Compatibility Effect	1	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	144	$F(1, 141) = 3.08$	$p = .081$	$t = 1.755$ Effect direction: positive	No delay	We thank Michael Kaschak for letting us know the exact F-value of the interaction of Sentence Direction x Response Direction.
Glenberg et al., 2008	Processing Abstract Language Modulates Motor System Activity	1	italian	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	20	$F(1, 19) = 5.02$	$p = .037$	$t = 2.241$ Effect direction: positive	No delay	
Borreggine & Kaschak, 2006	The Action-Sentence Compatibility Effect: It's All in the Timing	1	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	48	$F(1, 44) = 7.870$	$p = .008$	$t = 2.805$ Effect direction: positive	No delay	
		2	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	48	$F(1, 44) = .273$	$p = .604$	$t = .523$ Effect direction: positive	With delay	We thank Michael Kaschak for letting us know the exact F-value of the interaction of Sentence Direction x Response Direction.
		3	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	48	$F(1, 44) = .81$	$p = .373$	$t = .900$ Effect direction: negative	With delay	We thank Michael Kaschak for letting us know the exact F-value of the interaction of Sentence Direction x Response Direction.
		4	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	48	$F(1, 44) = 1.53$	$p = .223$	$t = 1.237$ Effect direction: negative	With delay	

Bergen & Wheeler, 2005	Sentence Understanding Engages Motor Processes	1	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	51	$F(1, 51) = 4.31$	$p = .043$	$t = 2.076$ Effect direction: positive	No delay
Glenberg & Kaschak, 2002	Grounding language in action	1	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	35	$F(1, 34) = 7.75$	$p = .009$	$t = 2.784$ Effect direction: positive	No delay
		2A	english	Button press	Away sentence – away arm movement; Toward sentence- toward arm movement	within	70	$F(1, 68) = 3.72$	$p = .058$	$t = 1.929$ Effect direction: positive	No delay