Guidelines for Reporting Action Simulation Studies (GRASS): proposals to improve reporting of research in Motor Imagery and Action Observation

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Abstract

Researchers from multiple disciplines have studied the simulation of actions through motor imagery, action observation, or their combination. Procedures used in these studies vary considerably between research groups, and no standardized approach to reporting experimental protocols has been proposed. This has led to under-reporting of critical details, impairing the assessment, replication, synthesis, and potential clinical translation of effects. We provide an overview of issues related to the reporting of information in action simulation studies, and discuss the benefits of standardized reporting. We propose a series of checklists that identify key details of research protocols to include when reporting action simulation studies. Each checklist comprises A) essential methodological details, B) essential details that are relevant to a specific mode of action simulation, and C) further points that may be useful on a case-by-case basis. We anticipate that the use of these guidelines will improve the understanding, reproduction, and synthesis of studies using action simulation, and enhance the translation of research using motor imagery and action observation to applied and clinical settings.

Keywords: Action observation system; Action simulation; Mental imagery; Mirror neurons; Movement control; Motor imagery; Motor simulation; Action Observation and Motor Imagery, AOMI, AO+MI.

Conflicts of Interest: None

1 Introduction

Action simulation (i.e. the internal representation of motor programs without overt movement; for detailed discussion see Jeannerod, 2001) is a topic of longstanding scientific interest (James, 1890). Work in this area has primarily examined the simulation of actions through motor imagery (i.e. imagining executing an action without physically performing it), action observation (i.e. watching movements being performed), or both combined (i.e. observing an action while simultaneously imagining the feelings associated with performing it, sometimes referred to as "action observation + motor imagery", "AOMI", or "AO+MI"; Vogt et al., 2013). Action simulation has been studied extensively across a wide range of disciplines including fundamental studies in neuroscience (e.g. Fadiga et al., 1999, 1995), applied work on athletic performance (e.g. Cumming and Eaves, 2018; Holmes and Collins, 2001), and skill acquisition (e.g. Frank et al., 2014; Lotze and Halsband, 2006; Williams and Gribble, 2012). Translational work has examined the use of action simulation in rehabilitation (e.g. Jackson et al., 2001, but see also Ietswaart et al., 2011), brain computer interfaces (e.g. Chaudhary et al., 2016), and neurofeedback (e.g. Liew et al., 2016). This multidisciplinary interest across the fields of fundamental, applied, and translational work has led to considerable growth and continued interest in the use of action simulation.

While several frameworks provide suggestions on how to develop experimental procedures for action simulation studies (Holmes and Collins, 2001; Macintyre et al., 2013; Ste-Marie et al., 2012; Williams et al., 2013; Wright et al., 2021), there is little work in relation to how best to *report* the protocols used in individual studies (Goginsky and Collins, 1996; Morris et al., 2005). This is notable as recent work has identified that critical details allowing the full assessment, replication, and translation of previously used protocols are reported inconsistently in the literature (Hardwick et al., 2018; Silva et al., 2020). Inspired by work aiming to standardize reporting approaches in other scientific domains (Chipchase et al., 2012; Moseley et al., 2002; Quintana et al., 2016), we consider the challenges presented by inconsistencies in the literature, and propose a set of guidelines to help standardize the reporting of action simulation studies.

2 Issues with the existing literature

2.1 Inconsistent Terminology

The terminology used to describe motor imagery and action observation protocols differs considerably between studies (see Table 1). For example, while it is generally agreed that the term “motor imagery” refers to imagining the performance of a movement, similar terms such as “Mental Practice” (often used to describe the use of motor imagery to train over multiple sessions), “Action Imagery” (Dahm et al., 2022), or the more general term “Mental Imagery” (which could equally refer to non-motor imagery) are also used to refer to such tasks (for discussion related to this point see Ladda et al., 2021). Importantly, from these terms alone, the exact content and sensory modality of the Imagery is not always fully clear; they can refer to the use of Visual Imagery (i.e. imagining ‘seeing’ the movement), Kinesthetic Imagery (i.e. broadly defined as imagining ‘feeling’ the movement, which can include somatosensory components such as proprioception and tactile elements, and is sometimes referred to by synonyms such as Somatomotor Imagery), a combination of these modalities, or other possibilities (e.g. more complex multisensory imagery using auditory, gustatory, and/or olfactory components, or imagery relating to motivation and arousal, etc.). This detail is important as performing the same task while engaging in different sensory modalities of imagery can lead to significant differences in behavior and neurophysiological activity (Guillot et al., 2009; Hardy and Callow, 1999; Jiang et al., 2015; Kilintari et al., 2016; Lee et al., 2019; Seiler et al., 2015; Stinear et al., 2006).

Similar issues to those described above also exist for action observation and AOMI, and are described in greater detail later in the manuscript. Consequently, if a study reports that participants performed “motor imagery”, “action observation”, or “AOMI” without further qualification, it is possible for the reader to misinterpret the protocol being used.

Table 1: Glossary providing a general summary of terms that are frequently used in the action simulation literature. Importantly, we do not suggest that this glossary be considered a ‘definitive standard’ to which all other articles must conform, as researchers in different groups and disciplines may have good reason to prefer differing terminology. Instead, we advocate that researchers should provide a clear operational definition of such terms on a paper-by-paper basis. This allows researchers the flexibility to describe their own research using their own preferred terms, while also ensuring that readers are provided with an immediately accessible definition within the same manuscript.

Glossary: cross-referenced terms are underlined	
Term	**Definition**
Action Simulation	The internal representation of motor acts without overt movement. Used here as an umbrella term covering the use of <u>motor imagery</u>, <u>action observation</u>, or their combination through ‘<u>AOMI</u>’. The term ‘action simulation’ therefore combines a wide range of different neural and theoretical mechanisms thought to include both overlapping and distinct components (for further discussion see Jeannerod, 2001; Hardwick et al., 2018).
Motor Imagery Action Imagery	Imagining executing an action without physically performing it. This can involve a multisensory simulation of the action, with the

	aspects of the visual imagery and/or kinesthetic imagery being most frequently discussed in the literature.
Action Observation	Watching movements being performed. See also entries on perspective.
AOMI AO+MI	Abbreviation of ‘Action Observation + Motor Imagery’; typically defined as observing an action while simultaneously imagining the feelings associated with performing it. Here the use of action observation generally replaces the use of visual imagery; consequently, ‘motor imagery’ in this context typically refers more specifically to kinesthetic imagery.
Visual imagery	In the context of motor imagery, visual imagery typically refers to imagining ‘seeing’ a movement being performed by constructing mental images or ‘pictures’ in the mind. In the broader literature visual imagery can also refer to generating images without referring to biological actions (e.g. imagining an object or landscape). See also entries on perspective.
Kinesthetic imagery Kinaesthetic imagery Somatomotor Imagery	Imagining ‘feeling’ a movement, which can include somatosensory components such as proprioception and tactile elements.
First person perspective Internal perspective Egocentric perspective	Use of a vantage point in which an action is imagined or observed as though viewed through the eyes of the performer (see also Figure 1). In certain cases these terms refer to a combination of both first person visual imagery and simultaneous kinesthetic imagery. In the present manuscript the use of the term ‘first person visual perspective’ refers specifically to visual imagery,

	allowing further specification about the use/absence of simultaneous kinesthetic imagery.
Third person perspective External perspective Allocentric perspective	Use of a vantage point as though observing the action as an onlooker (see also Figure 1). These terms generally refer to the use of visual imagery alone (contrary to first person/internal/egocentric perspective).

Different terms are also used to describe apparently equivalent conditions in the action simulation literature. For example, the visual perspective from which actions are imagined or observed can be equivalent to seeing the action through the eyes of the performer, or from another vantage point. In the literature this difference has been variously labeled as comparing 'Internal vs External' (Pilgramm et al., 2010), 'First person vs Third person' perspective (Fourkas et al., 2006), or 'Egocentric vs Allocentric' (Shmuelof and Zohary, 2008) conditions. While it would be reasonable to assume that these terms are interchangeable, this is not always the case; in the literature the term 'third person imagery' has been used to refer not only to the viewpoint, but also the agent of the action (i.e. imagining *yourself* performing a movement, or imaging *another person* performing a movement; Fourkas et al., 2006). Further complexity is introduced when considering that the term 'external perspective' could equally refer to multiple different vantage points (see Figure 1). Again, such details are important as prior work on action simulation has shown that the viewpoint from which an action is imagined or observed can significantly modulate neurophysiological activity (Fourkas et al., 2006; Jackson et al., 2006) and behavior (Callow et al., 2019; Hardwick and Edwards, 2012; Lawson et al., 2016; Vogt et al., 2003). Such failure to provide details can also make it difficult for the reader to accurately comprehend the procedures used in the study (Holmes and Calmels, 2008).

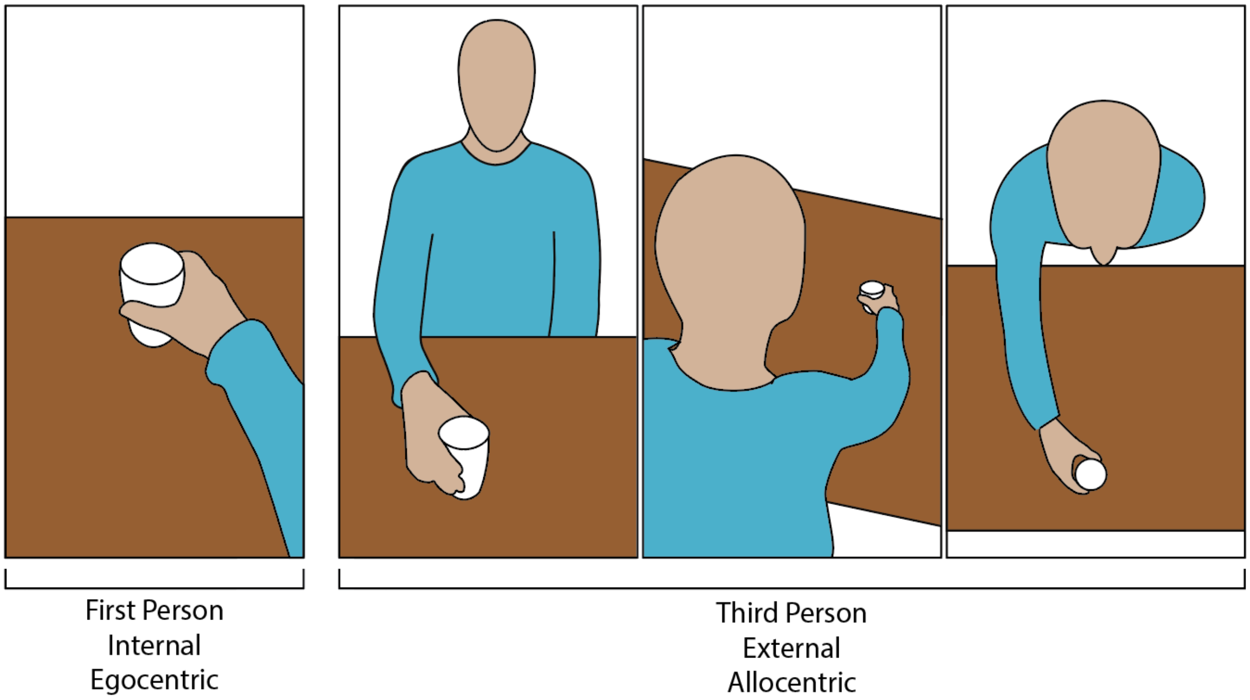

Figure 1: Examples of different visual perspectives that could be taken during action simulation. While a "first person" visual perspective is readily understood, the term "third person" visual perspective is more ambiguous due to the many degrees of freedom available in viewing position, distance, etc. Including clear descriptions and/or images illustrating the viewpoints used is recommended in order to reduce this ambiguity.

2.2 Underreporting of task details

Prior work has identified that the underreporting of task details is a common issue in the action simulation literature. A review of recent papers indicated that 64% of studies using motor imagery do not provide enough information to discern whether participants were instructed to use kinesthetic imagery, visual imagery, or a combination of both (Van Caenegem et al., 2022). Similarly, a meta-analysis of neuroimaging studies found that approximately 66% of studies using motor imagery and 20% of studies using action observation did not provide a description or figure that allowed the visual perspective used to be determined (Hardwick et al., 2018).

These details are not trivial because - as noted previously - prior research has shown significant differences between behavior and brain activity for action simulation using different modalities and perspectives (Fourkas et al., 2006; Guillot et al., 2009; Hardy and Callow, 1999; Jackson et al., 2006; Jiang et al., 2015; Kilintari et al., 2016; Lee et al., 2019; Seiler et al., 2015; Stinear et al., 2006). Underreporting of details also leads to difficulties when attempting to review the literature - an issue which has been specifically noted in recent systematic reviews related to motor imagery and related fields (Baniqued et al., 2021; Silva et al., 2020).

3 Checklists for Essential and Suggested Details

Given the discussion above, developing and adopting a standardized procedure for reporting information from studies of action simulation is highly recommended. To this aim we have developed separate checklists for Motor Imagery, Action Observation, and AOMI which provide prompts for points to include when conducting and reporting studies (see Appendices). To avoid placing an unnecessary burden on researchers, these checklists do not provide an exhaustive list of all potential considerations for action simulation studies. Instead, each checklist has three parts. Part A prompts authors to include key information about their methodological and statistical procedures, and should apply to the vast majority of action simulation research. As many of these points may be considered fundamental to study reporting in most disciplines, they are not discussed at length in the main manuscript; for a broad overview of these points (including discussion of their relevance to action simulation; note in particular that issues such as prior experience, instructions, and order of testing may be particularly relevant to action simulation studies) see the appendices for this article. Part B requests key details relating to specific aspects of the modality of action simulation being used (i.e. Motor Imagery, Action

Observation, or AOMI; see also Table 2, which summarizes the main strengths and limitations of these different forms of Action Simulation, and may therefore help researchers to identify further reporting considerations. Part C presents additional, optional considerations that may apply to a given form of action simulation on a case-by-case basis (often depending on the specific experimental protocol and apparatus used in the study; for more information on frequently used procedures in the action simulation literature see Supplementary Table 1), and are left to the author's discretion. The following text provides an overview of these points, and highlights reasons for their inclusion.

3.1 Motor Imagery

3.1.1 Modality of Imagery

While studies will often state that participants were asked to perform 'motor imagery', this does not necessarily provide all the detail that is useful for future replication. In particular it is important to clarify whether participants were instructed to engage in kinesthetic motor imagery, visual motor imagery, or their combination, given their specific strengths and limitations (see Table 2). While some frameworks assume an intrinsic link between the visual and kinesthetic modalities (e.g. "Internal" imagery often refers to a combination of first person visual and kinesthetic imagery, compared to "External" imagery which involves only third person visual components; Mahoney and Avener, 1977), other frameworks consider visual and kinesthetic modalities to be separable dimensions (e.g. motor imagery could be performed purely kinesthetically (Stinear et al., 2006), purely visually using either a first or third person perspective (Hall and Martin, 1997), or through combinations of first person visual and kinesthetic imagery, and even combined third person visual and kinesthetic imagery; Hardy and Callow, 1999). Clarifying the sensory modalities instructed during motor imagery is important as prior work indicates the differing modalities affect behavioral and neurophysiological responses

(Guillot et al., 2009; Jiang et al., 2015; Kilintari et al., 2016; Lee et al., 2019; Seiler et al., 2015; Stinear et al., 2006). The use of further sensory modalities may also be considered; in particular, the sport-science literature argues that the vividness and efficacy of imagery can be enhanced using multisensory simulation (e.g. including haptic, auditory, olfactory, and/or gustatory components; Holmes and Collins, 2001). This could be considered through direct instructions to participants, and/or asking about the use of multisensory imagery when debriefing participants.

3.1.2 Visual Perspective

Visual aspects of motor imagery can be achieved using a multitude of different possible viewing perspectives and vantage points (see Figure 1). This can make it difficult for readers to understand, for example, exactly what is meant if the term ‘third person perspective’ is used alone. When describing the visual perspective that is to be taken, a thorough description - accompanied by an appropriate illustration if possible to depict vantage point - can help to provide enough detail to allow accurate comprehension of the experimental procedures.

3.1.3 Assessments of Image Quality and/or Imagery Ability

Differences in participant’s general ability to use motor imagery has been linked with differences in brain activity during motor imagery tasks (Guillot et al., 2008), and is a potentially problematic source of between-participant variability in research studies. The ability to produce imagery is not uniform across the population, and recent work indicates that 2-5% of individuals have ‘Aphantasia’ - a condition in which voluntary imagery is markedly impaired or entirely absent (Dance et al., 2022; Faw, 2009; Zeman et al., 2015). Beyond this, participants may be able to use motor imagery, but struggle with specific components of the image (e.g. timing, controllability, etc; see Cumming and Eaves, 2018; Kraeutner et al., 2020). Such issues can be identified through assessments of the quality of participant's motor imagery, or through post-test debriefings. Indeed, depending on the specific experimental question being examined, it may be appropriate to use imagery ability as an inclusion or exclusion criterion (e.g. to rule out participants with aphantasia or specifically identify participants with low imagery ability in order to examine training interventions; Williams et al., 2013). Imagery ability has been examined through numerous validated questionnaires; researchers are therefore advised to carefully consider which of the available assessments is most relevant to their particular study (e.g. Guillot and Collet, 2005; Malouin et al., 2007; Roberts et al., 2008; Williams et al., 2012). Neurophysiological evidence also indicates that greater self-reported imagery ability is associated with greater use-dependent plasticity during motor imagery training interventions (Yoxon et al., 2022), highlighting the importance of considering individual differences in imagery ability. We note, however, that the classification of imagery ability remains challenging; for example, while questionnaires provide an imagery ability score, there is relatively little normative data allowing classification of 'good' or 'poor' imagery ability. While several papers have proposed different categorizations of imagery ability (e.g. Collet et al., 2011; Cumming and Eaves, 2018; Heremans et al., 2013; Suica et al., 2022; Williams et al., 2015), there is limited consensus regarding the boundaries between different groups of ability levels; as such, these classifications remain relatively subjective. As there is no current gold-standard for classifying imagery ability (see Supplementary Table 1 for an overview), developing more objective classifications (e.g. through data-driven assessment of large samples of participants) remains an interesting question for future research.

3.2 Action Observation

3.2.1 Visual Perspective

Similar to motor imagery, action observation can use a multitude of different vantage points (see Figure 1), making it difficult to interpret what exactly is meant when descriptions such as ‘third person perspective’ are used alone. However, in contrast to motor imagery, studies using action observation can easily include examples of their actual stimuli in figures, and can potentially include their full original stimuli in supplementary materials or online repositories. Text descriptions are also encouraged to help clarify details, especially if multiple different viewing perspectives are included.

For studies involving imitation, it can be particularly useful to describe the position of the actor performing the movement in relation to the participant, and how the movement was matched. For example, when standing directly opposite a participant, there is greater spatial congruence between the movement of the actor and the participant if the action is presented as through looking in a mirror (e.g. an experimenter moving their left hand would be matched by a participant acting with their right hand). This issue of spatial congruence may be particularly important in populations such as children (Holmes and Calmels, 2008), or when working in rehabilitation (Hogeveen et al., 2015). Reporting such details is therefore useful to help better understand the exact paradigm and procedures being used in the study.

3.2.2 Viewing Conditions (Live vs Pre-recorded performance, Interpersonal Interaction, Virtual Reality and other emerging technologies)

Action stimuli can be presented to participants either by a live model (e.g. demonstrated by an experimenter) or via a pre-captured performance (presented through videos, still images - see Kourtzi and Kanwisher, 2000; Rohbanfard and Proteau, 2013, etc). Each of these forms of presentation have different advantages (see Table 2). Live modeling includes social interaction that is not possible with pre-recorded stimuli, which provides greater ecological validity (Reader and Holmes, 2016; Risko et al., 2012), and there is evidence for stronger neural responses to live-modeled compared to pre-recorded actions (Järveläinen et al., 2001; Prinsen and Alaerts, 2019). Motion capture techniques can also be used to record the live performance of the experimenter, allowing a permanent record of the modeled actions. By comparison, pre-captured recordings allow more precise control over both the content and timing of events of the modeled action, and can be edited to suit the needs of the experiment. Given these differences, it is recommended that researchers clearly report how modeled actions were presented during the study. Any editing of pre-recorded actions (e.g. to create the illusion of movement from two still images, to remove certain components of the action, or to edit the action) should be documented. In particular, the kinematic profiles and biological plausibility of actions appear to be important modulatory factors in action observation (Stanley et al., 2007); it is therefore recommended to clearly document any changes that may modify these properties of observed actions. Moreover, capturing the details of the kinematics of observed movement stimuli using motion capture techniques can provide additional insight into the influence that the observed model has on the participant (Becchio et al., 2018). Researchers may also wish to consider including their stimuli/recordings of modeled actions in an online repository. This will help to fully clarify the stimuli used, and also allows their future use by other members of the scientific community (see the appendix section 1.2.2 on “Data Sharing and Open Science Practices”).

Recent advances in markerless motion tracking mean that kinematic information can now be extracted from pre-recorded videos, providing the potential for further in-depth analysis of the similarities between the observed model and the subsequent kinematics of participants.

As noted above, prior research indicates that interpersonal interaction can modulate action observation effects. Similarly, work in primates indicates that neural responses to observed actions differ when the same action is presented either inside or outside of the space within which the observer can act (Caggiano et al., 2009). Reporting the approximate distances between the observer and the modeled action could therefore enhance future examination of such effects.

While prior work suggests that live-performed actions may provide more compelling stimuli, recent developments in fields such as Virtual reality, Augmented Reality, and 360 degree video technology now allow opportunities for highly immersive action simulation experiences (Frank et al., 2022; Frank and Schack, 2020). At the time of writing this represents a relatively new and growing field of research. This means that questions such as whether interacting with a virtual character in 3D space can produce similar effects to interacting with an actual human remain open for future investigation. It is suggested that researchers working in these emerging fields not only consider the recommendations of this document, but also think carefully about key details that need to be reported in their publications that may be critical to the accurate replication and future translation of their experiments.

3.2.3 Observer attention, Engagement & potentially confounding use of motor imagery

Participants can observe actions passively (e.g. to simply observe the movement with no further intention), or can engage more actively with the action (e.g. observing in order to provide a specific response, such as imitating the movement or answering a question about the stimulus).

Prior research indicates that the intention with which actions are observed can have significant effects on corticospinal excitability and the extent of the brain network activated during action observation (Caspers et al., 2010; Hardwick et al., 2012). Instructions to attend to specific aspects of the movement can also modulate action observation effects (Bek et al., 2016) and brain activation during action observation (Zentgraf et al., 2005). More recent work has also indicated that participants in action observation studies may covertly engage in motor imagery without being instructed to do so, introducing a potential confound in studies of 'pure' action observation (Bruton et al., 2020; Franklin et al., 2020; Meers et al., 2020; Vogt et al., 2013). As such, it is recommended to report whether participants observed actions in a passive or active context, and to consider asking participants about their potential use and content of motor imagery during study debriefing (e.g. Bek et al., 2019).

3.2.4 Similarity between the Model and Observer (Ability levels and Demographics)

Differences in the abilities of the model and the observer represent an area of longstanding interest in research on action observation (for example, prior research has examined effects such as age (Raz et al., 1999; Schott, 2012), sex (Conson et al., 2020; Subirats et al., 2018) or model skill level; Rohbanfard and Proteau, 2011). As discussed in the general methods section (see appendix section 1.2), there is debate in the literature regarding whether the participant's own ability to perform observed movements leads to differences in action simulation (c.f. Calvo-Merino et al., 2005; Vannuscorps and Caramazza, 2016). Differing ability levels may be important for studies using action observation for training purposes. Studies examining motor learning through action observation may present novices with no prior experience with the task (e.g. Mattar and Gribble, 2005). The observer therefore sees a model going through the learning process, rather than the eventual desired level of expertise. Similarly, work with patients has argued that observing a high-performing person with a similar motor deficit may be more effective than observing the performance of an unimpaired model (Alsamour et al., 2018; Castiello et al., 2009). More general similarities and differences between the model and the observed (e.g. observing oneself vs another person, sex differences, etc) may further modulate these effects. It is therefore recommended that authors report any potential differences in ability between the model and the observer, and may also wish to consider reporting any differences between the demographics of the model and participants.

3.2.5 Synchronicity of the Observed Action and Response

The synchronicity between the observed stimulus movement and the participant's own response remains a relatively under-explored area. Research on motor learning indicates that introducing a delay between an observed and executed movement leads to greater retention during follow-up tests as compared to synchronous movement imitation (Weeks et al., 1996). Research on more fundamental questions in motor control, however, has not identified significant effects of synchronous compared to asynchronous action observation and execution (Hardwick and Edwards, 2012), though some effects presumably depend on simultaneous observation and execution (Kilner et al., 2003). There is also evidence that simultaneous observation and execution affects which elements (e.g. duration versus amplitude) of the observed movement are replicated (Bek et al., 2021). Consequently, it is recommended to report whether the observed movement and any required responses occurred synchronously, or to give the (approximate) delay between the movements as appropriate.

3.3 Combined Action Observation and Motor Imagery (AOMI)

3.3.1 Synchronous vs Asynchronous Simulations

There are numerous examples of studies administering simulation interventions that comprise both action observation and motor imagery, with their delivery being either synchronous (i.e. action observation and motor imagery at the same time; e.g., Marshall et al., 2020; Scott et al., 2018) or asynchronous (i.e. action observation then motor imagery; e.g., McNeill et al., 2020; Wilson et al., 2016). In this section we focus on issues specific to the former case (Eaves et al., 2022); for asynchronous procedures we refer the reader to the above sections on AO and MI with associated, separate GRASS checklists.

The synchronous use of action observation and motor imagery was made topical in a position paper by Vogt et al. (2013). This paper introduced the term 'AOMI', where a performer observes a movement demonstration while simultaneously imagining performing an action. The instructions for the AO- and MI-components of AOMI normally include those of “pure” action observation and “pure” motor imagery, and participants might benefit from first being introduced to each form of action simulation separately before being asked to engage in them together. Thus, the above sections on action observation and motor imagery can also apply to AOMI, but a few aspects arising from the synchronous engagement deserve special attention. To avoid confusion, we recommend that in future publications authors make explicit reference to whether action observation and motor imagery were administered synchronously or asynchronously (as each approach has its own strengths and limitations, see Table 2), and that the terms 'AOMI' or ‘AO+MI’ be reserved to refer only to synchronous applications.

3.3.2 Types of AOMI (Congruent, Coordinative, and Conflicting)

Prior research on AOMI has focused primarily on scenarios where the same action is observed and imagined (termed 'congruent AOMI' by Vogt et al., 2013). In contrast, forms of AOMI where participants observe one action and imagine a different action have received less attention. These can be subdivided into 'coordinative AOMI', where the observed and imagined actions are different but related (e.g. observing the ballroom dance routine performed by their partner, while simultaneously imagining their own corresponding movements) and a form of 'conflicting AOMI' where the observed and imagined actions are largely unrelated (e.g., observation of grasping and imagery of rotating an object). While coordinative AOMI is of interest both regarding practical applications in skill acquisition and basic research (e.g. Bruton et al., 2020; McNeill et al., 2021; Meers et al., 2020), conflicting AOMI is presumably mainly of interest to address specific questions in basic research (e.g., Eaves et al., 2014, 2016, 2012). While it is usually possible to determine which type of AOMI a study used, it is recommended that authors report a clear description of the contents of action observation and motor imagery, being mindful that congruent AOMI is not the only form of AOMI. Note also that the term ‘congruent’ in this context refers only to the observed and imagined action being the same, and may involve discrepancies between the AO and MI components in several other respects (e.g., observation of movement execution by another person whilst imagining self-execution, observing from a third person visual perspective while engaging in kinesthetic imagery from a first person perspective, etc).

3.3.3 Visual Perspective and Spatial Considerations

The choice of visual perspective for action observation during AOMI deserves special attention as the instruction provided for simultaneous motor imagery typically emphasizes kinesthetic motor imagery. Studies using AOMI have presented videos filmed from first person and third person visual perspectives, with the choice of perspective presumably being influenced by the task. For example, AOMI studies examining walking (e.g. Kaneko et al., 2018; Marusic et al., 2018) or balance (e.g. Mouthon et al., 2015; Taube et al., 2015) have typically used third person visual perspectives, presumably as a first person perspective would provide little-to-no biological movement stimuli with which the participant could synchronize their imagery. By contrast, other tasks such as golf putting have been presented using both first person (Marshall and Wright, 2016) and third person (McNeill et al., 2021) visual perspectives. Both perspectives offer different advantages; a first person perspective closely resembles visual information during action execution, and may contribute to an illusion of self-execution that could facilitate kinesthetic imagery, while third person perspectives typically provide more visual information with which the participant could synchronize their imagery (Wright et al., 2021).

In relation to the use of different perspectives, both action observation and motor imagery can involve representation of the action-relevant space (Jeannerod, 1994), including aspects such as relevant body parts or objects. This space can overlap to varying extent with the visual space of the observed actor. For example, in a scenario where the participant watches an actor reaching for an object from a third person perspective, motor imagery can involve the very same object, or could be directed to a similar object in a different location. Likewise, while first person perspectives can promote a fusing of the observed body parts with one's own body schema (giving rise to the aforementioned illusion of self-execution), non-overlapping spaces are also conceivable.

In summary, as well as providing figures illustrating the visual perspective used, authors of AOMI papers may consider including a discussion of why a particular perspective was chosen, and consider the overlap between the spaces involved in the observed and imagined movements.

3.3.4 Nature of the Imagery Instructions

As the action observation component of AOMI provides clear visual input, the imagery instructions typically emphasize the use of synchronous kinesthetic imagery (see Wright et al., 2021 for guidelines on developing imagery instructions for use in AOMI). While the majority of AOMI research reports imagery instructions that emphasize imagining the feelings or sensations of the movement, this is not always stated explicitly (Ladda et al., 2021; Munzert and Zentgraf, 2009; Zentgraf et al., 2005). Similar to research on “pure” action observation or motor imagery, the exact instructions provided to participants are not always reported. Both these issues can make it difficult for readers to fully understand the AOMI protocol that was administered. Authors conducting AOMI studies are therefore encouraged to emphasize kinesthetic imagery instructions when conducting AOMI research, and to include the exact wording of the imagery instructions as provided to the participants (in the manuscript, supplementary materials, or a linked online repository).

3.3.5 Participant Imagery Ability Characteristics

The ability to produce voluntary imagery varies between individuals (for more detail see the section on Motor Imagery), which presents an important consideration in AOMI research. This issue may be particularly prevalent in clinical populations, such as stroke or developmental coordination disorder, where AOMI interventions have been employed previously (Marshall et al., 2020; Scott et al., 2020; Sun et al., 2016) but where imagery ability is known to be impaired (Ewan et al., 2010; Reynolds et al., 2015). AOMI also requires active effort to keep the motor imagery synchronized with the observed action; this is likely to require additional neurocognitive resources (Eaves et al., 2016), and again represents an important consideration for work with clinical populations (see Table 2). Several AOMI studies have addressed these issues by employing self-report imagery ability assessments (e.g. Bruton et al., 2020; Eaves et al., 2016; Scott et al., 2018) but such checks are not always included in AOMI research. Authors of AOMI research are therefore recommended to report at least the kinesthetic imagery ability scores for their participants, or employ post-experiment manipulation checks to verify that participants were able to perform AOMI as instructed (e.g. Bek et al., 2019).

4 Conclusions

Studies examining action simulation (which includes the fields of motor imagery, action observation, or their combination) often underreport details of their procedures. This leads to problems understanding and replicating previous work, and is likely to impair the translation of this work to clinical and applied settings. To address this problem, we have designed several checklists for studies involving motor imagery, action observation, or their combined use through “AOMI”. These checklists highlight important details that are recommended for inclusion in publications, and the vast majority of these points do not require significant additional work on the part of the authors. Further additional factors worthy of consideration on a case-by-case basis are also included and addressed in the body text of the current manuscript. We propose that adhering to these guidelines will improve the comprehension of experimental details, future synthesis of the literature, and the development of robust procedures that can be translated to clinical settings. We anticipate the adoption of these Guidelines for Reporting Action Simulation Studies (GRASS) will significantly enhance the quality of reporting in this field.

Motor Imagery **GRASS checklist**

Part A: Essential items for general study reporting

#	Item	Pages
A1	Are participant characteristics (age, sex, handedness, experience with similar tasks, vision, clinical details, etc) included for the final study sample/groups?	
A2	What instructions were provided? How were they delivered (spoken, written, etc)?	
A3	Were standard instructions used (i.e. a script, information sheet etc)? Is this available to readers (in the manuscript, supplementary materials, an online repository, etc)?	
A4	Was adherence to instructions monitored (e.g. EMG recordings, post test questionnaires, repeated instructions, manipulation checks, etc)?	
A5	Do statistical comparisons include the average and standard deviation or standard error of the mean for the groups/conditions?	
A6	Is the ‘dose’ used in the study clearly defined (i.e. sessions, blocks, trials, duration, etc)?	

Part B: Essential items relating specifically to motor imagery

B1	Were participants instructed to use kinesthetic imagery, visual imagery, or a combination of both?	
B2	If visual imagery was used, is the visual perspective (1st person, 3rd person) stated?	
B3	If 3rd person imagery was used, is the vantage point specified? Is it illustrated?	
B4	Were participants previously familiar with motor imagery (e.g. sports practice, prior participation in experiments)?	

Part C: Discretionary Items (to be included as appropriate on a case-by-case basis)

C1	Are study materials/data/code openly available (including a link to a repository)?	
C2	Were imagery instructions based on a framework (e.g. PETTLEP, LSRT)? If so, how?	
C3	Was imagery ability/quality assessed (e.g. questionnaires, chronometry)?	
C4	Was the participant’s body posture matched with the action(s) they imagined (e.g. were imagined/actual postures matched, mirrored, etc)?	
C5	Was movement during imagery instructed/allowed (e.g. dynamic motor imagery)?	
C6	Were other modalities of imagery (e.g. auditory, haptic, olfactory, gustatory) instructed or reported by participants?	

Action Observation **GRASS checklist**

Part A: Essential items for general study reporting

#	Item	Pages
A1	Are participant characteristics (age, sex, handedness, experience with similar tasks, vision, clinical details, etc) included for the final study sample/groups?	
A2	What instructions were provided? How were they delivered (spoken, written, etc)?	
A3	Were standard instructions used (i.e. a script, information sheet etc)? Is this available to readers (in the manuscript, supplementary materials, an online repository, etc)?	
A4	Was adherence to instructions monitored (e.g. EMG recordings, post test questionnaires, repeated instructions, manipulation checks, etc)?	
A5	Do statistical comparisons include the average and standard deviation or standard error of the mean for the groups/conditions?	
A6	Is the ‘dose’ used in the study clearly defined (i.e. sessions, blocks, trials, duration, etc)?	

Part B: Essential items relating specifically to action observation

B1	Is the visual perspective used (e.g. 1st person, 3rd person, a combination) stated? Is the vantage point/camera position shown with an image/illustration?	
B2	Are model characteristics (e.g. sex, expertise) described/illustrated?	
B3	Were observed actions presented via a live model or pre-recorded?	
B4	Were participants previously familiar with using action observation for a specific purpose (e.g. reviewing film in sports, prior participation in research)?	

Part C: Discretionary Items (to be included as appropriate on a case-by-case basis)

C1	Are study materials/data/code openly available (including a link to a repository)?	
C2	Was the participant’s body posture matched with the action(s) they saw (e.g. were observed/actual postures matched, mirrored, etc)?	
C3	If a pre-recorded performance was observed, was it edited? (e.g. adding/removing video frames, use of a computer-generated character model, etc).	
C4	Did observed movements have biologically valid kinematics?	
C5	Were participants asked about their potential use of (deliberate or spontaneous) motor imagery during action observation?	
C6	At what (approximate) distance were actions presented from the observer? Did the ‘action space’ for observed actions overlap with their own “action space”?	

Action Observation & Motor Imagery (AOMI) **GRASS checklist**

(NOTE: These points consider synchronous AO and MI; see their respective individual lists for asynchronous use)

Part A: Essential items for general study reporting

#	Item	Pages
A1	Are participant characteristics (age, sex, handedness, experience with similar tasks, vision, clinical details, etc) included for the final study sample/groups?	
A2	What instructions were provided? How were they delivered (spoken, written, etc)?	
A3	Were standard instructions used (i.e. a script, information sheet etc)? Is this available to readers (in the manuscript, supplementary materials, an online repository, etc)?	
A4	Was adherence to instructions monitored (e.g. EMG recordings, post test questionnaires, repeated instructions, manipulation checks, etc)?	
A5	Do statistical comparisons include the average and standard deviation or standard error of the mean for the groups/conditions?	
A6	Is the 'dose' used in the study clearly defined (i.e. sessions, blocks, trials, duration, etc)?	

Part B: Essential items relating specifically to AOMI

B1	Is the visual perspective used (e.g. 1st person, 3rd person, a combination) stated? Is the vantage point/camera position shown with an image/illustration?	
B2	Are model characteristics (e.g. sex, expertise) described/illustrated?	
B3	Were observed actions presented via a live model or pre-recorded?	
B4	Were participants previously familiar with using action observation/motor imagery for a specific purpose (e.g. in sports practice, prior participation in research)?	
B5	Were participants instructed to use kinesthetic imagery, visual imagery (e.g. complementing the observed action), or a combination of both?	

Part C: Discretionary Items (to be included as appropriate on a case-by-case basis)

C1	Are study materials/data/code openly available (including a link to a repository)?	
C2	Was the participant's body posture matched with the action(s) they saw/imagined (e.g. were observed/imagined/actual postures matched, mirrored, etc)?	
C3	If a pre-recorded performance was observed, was it edited? (e.g. adding/removing video frames, use of a computer-generated character model, etc).	
C4	Did observed movements have biologically valid kinematics?	
C5	At what (approximate) distance were actions presented from the observer? Did the 'action space' for observed actions overlap with their "peripersonal space"?	
C6	Was imagery ability/quality assessed (e.g. questionnaires, chronometry)?	
C7	Were imagery instructions based on a framework (e.g. PETTLEP, LSRT)? If so, how?	
C8	Were the observed and imagined actions congruent (the same), coordinative, or conflicting?	

Author Contributions

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Supplementary Materials: Guidelines for Reporting Action Simulation Studies (GRASS): proposals to improve reporting of research in Motor Imagery and Action Observation

The following sections discuss points relating to study design. As several of these points are not specific to action simulation (applying equally well across several of the cognitive sciences), they are therefore not included in our main manuscript. We note, however, that even fundamental study details are sometimes absent from the published literature (see Section 2 of the main manuscript). We therefore include discussion of these topics in order to 1) provide further explanation for the items in part A of the GRASS checklists, and 2) to provide a ‘primer’ to help readers with more limited experience with action simulation techniques.

1.1 General Recommendations: Methods

1.1.1 Participant Characteristics

Several traditionally reported participant characteristics have been shown to interact with action simulation effects (e.g. age (Raz et al., 1999; Schott, 2012), sex (Conson et al., 2020; Subirats et al., 2018), and handedness (Crotti et al., 2022; Zapała et al., 2021)). This detail should always be given with respect to the final study sample (after any exclusions), and should be included for separate groups that complete the study where applicable.

1.1.1.1 Prior experience with action simulation

There is also scope to consider the familiarity that participants have with action simulation techniques. For example, a study focusing on student athletes may involve a population that is already familiar with motor imagery, or reviewing film recordings via action observation, as part of their preparation for competition. A study of the ‘general’ population that happens to include athlete and non-athlete participants could therefore unknowingly include participants with varying levels of experience with action simulation. The best way to measure and control for these factors will depend on the design of the specific study; for example, if a study is interested in examining a novice population, excluding participants that report having previous experience with action simulation techniques (analogous to studies of motor learning excluding participants with experience with similar motor tasks, e.g. Gann et al., 2021) may be preferable.

1.1.1.2 Prior knowledge/experience with behavioral tasks

Prior knowledge can modulate action simulation effects (Hudson et al., 2016), and previous work has also argued that the participant's "motor repertoire" and their familiarity with specific observed actions strongly influences action simulation (Aglioti et al., 2008; Calvo-Merino et al., 2005; but see also Vannuscorps and Caramazza, 2016). Establishing the participant's baseline level of skill in the behavioral task, and screening for experience that may affect their performance (e.g. excluding pianists or professional typists from motor learning tasks involving sequences of finger movements) can help to produce a more homogenous sample. Alternatively, conducting analyses on participants with differing levels of expertise with a behavioral task can be an interesting approach to examining how prior experience affects action simulation processes (Abernethy et al., 2008; Frank et al., 2023).

1.1.2 Instructions

Ensuring experimental instructions are understood can be challenging for abstract tasks such as those using motor imagery. To provide common ground, it can be useful to give participants a general introduction to action simulation in order to help them understand what it involves, and why it is being studied (e.g. potential benefits to performance/rehabilitation). Providing instructions using a standardized script, followed by the chance for the participant to ask questions, provides a uniform approach to promote clear understanding. This issue is particularly important for motor imagery, as instructions can be delivered in a number of ways (a series of images, written or auditory scripts, etc). Existing frameworks for delivering and developing motor imagery can serve as a reference point when developing instructions (Holmes & Collins, 2001; Macintyre et al., 2013; Williams et al., 2013; Wright et al., 2021). Instructions explicitly stating the goal/intention of the task (e.g. Observing an action with the intention to later imitate it; Hardwick et al., 2012) help to remove potentially ambiguous points that may affect action simulation. Where possible, including the full text of the instructions in the manuscript, supplementary materials, and/or an online repository ensures that all relevant details are included, and improves the potential to replicate and extend the effects presented.

1.1.3 Adherence to Instructions

Once instructions are provided, it can be useful to consider approaches to monitor how well participants adhere to them. The exact procedure used to assess this will vary from study-to-study, and a wide range of approaches are possible. For example, this could include the recording of electromyography during motor imagery and action observation conditions to detect overt movements; this measure is frequently used in MRI studies to differentiate between actual motor activity and imagined movements, enhancing the reliability of results (e.g. (Berman et al., 2012). Other approaches include the use of post-test questionnaires or manipulation checks, the use of eye-tracking, or the use of catch trials or questions to ensure attention is maintained throughout the experiment (for examples see Bruton et al., 2020; Hardwick et al., 2012; Williams et al., 2013; Wright et al., 2018) and potentially other physiological markers (cardiac frequency, electrodermal activity; see Collet et al., 2011). Debriefing questionnaires may also be of interest in situations where potential confounds can occur (e.g. implicit effects such as if a participant found themselves spontaneously using motor imagery in a study that only instructed them to use action observation; (Meers et al., 2020).

1.1.4 Congruence between participant's state and simulated actions

The same action can be simulated in multiple different settings; for example, a soccer penalty kick could be imagined while standing on the pitch just before physically performing the kick, or while lying in a Magnetic Resonance Imaging scanner. Influential models argue that increasing the similarity between the participant's current state and the actions that they imagine enhances the effects of imagery (Guillot et al., 2021, 2013; Holmes and Collins, 2001). Related studies have examined the effects of factors such as the participant's posture (Beauchet et al., 2018; Guilbert et al., 2021; Holmes et al., 2006; Lorey et al., 2009), tactile feedback (Mizuguchi et al., 2013, 2011, 2009), or physical movement (e.g. dynamic motor imagery; see Guillot et al., 2021) during action simulation. Researchers may therefore wish to consider remarking on the congruence between the participant's current physical state relative to simulated actions where appropriate.

1.1.5 Choice of control conditions/groups

The use of appropriate control conditions and groups is an important consideration for action simulation studies. Beyond their specific requirements, motor imagery and action observation both involve non-specific factors such as increased demands on attention and concentration compared to rest or simple fixation. These demands call for specific control conditions (for further discussion see Loporto et al., 2011; Naish et al., 2014) and considerations regarding their scheduling during the experiment (e.g. Marshall et al., 2020; Marshall and Wright, 2016). Action simulation effects are also influenced by prior experience, which can range from extensive expertise acquired through years of training (Calvo-Merino et al., 2005) to possible issues relating to completing another condition or viewing a specific stimulus in the same experiment (c.f. (Rens et al., 2020; Senot et al., 2011). Consequently, authors may consider explicitly stating their rationale for the choice of whether control conditions are completed in separate blocks, interleaved with main experimental conditions (e.g. Gowen and Poliakoff, 2012), or performed by different groups of participants (Rens et al., 2020). Moreover, depending on the experimental design, authors may consider controlling for differences between physical and mental practice such as differences in feedback (Ingram et al., 2019; Wulf et al., 1995). It is therefore recommended that authors carefully consider their choices relating to control conditions/groups, and include discussion of why the controls used are appropriate in their manuscripts.

1.1.6 Clearly explaining the Amount/Dose of Action Simulation

Clearly explaining the overall exposure to action simulation is important for understanding the procedures used in a study. This can be provided by including a paragraph that states the number of sessions the participants completed, the number of blocks conducted per session, and the number of trials completed in each block of training, accompanied by an easy to understand illustration wherever possible (e.g. Bruton et al., 2020). Further details such as the duration of each block, helps to define the relative “dose” of the intervention. Consequently, we recommend including information about the dose both in terms of the number of trials completed (i.e. by session, block, condition etc), and also the overall time spent (i.e. duration of each session, duration of stimuli, inter-trial intervals, rest periods, etc).

Notably, the overall duration of action simulation may differ in certain conditions (for example, an expert may be much faster to complete the same task compared to a novice, or a person with a stroke could be much faster to perform a task with their unaffected limb compared to their affected limb; both these examples would lead to differences in the amount of time required to observe the performance of the same number of trials). Maintaining the overall session length by manipulating inter-trial intervals could help control for possible effects of fatigue etc. in such situations.

1.1.7 Choice of experimental procedures

Various experimental procedures have been used in the action simulation literature, including both behavioral and physiological methods. Each of these has its own strengths and limitations, which should be carefully considered based on the study’s aim. It is recommended to take into account which experimental procedures are the most appropriate for each specific research question and design, and their potential complementary use. Supplementary Table 1 summarizes the main strengths and limitations of most experimental procedures frequently utilized in the action simulation field.

Supplementary Table 1. Strengths and limitations of different experimental procedures related to Action Simulation.

Experimental Procedures	**Strengths**	**Limitations**
Behavioural Procedures		
Imagery Ability/Vividness Questionnaires	● Easy to administer. ● Short time to complete. ● Inexpensive measurement.	● Subjective measures. ● No gold-standard for classification (e.g. “good” vs “poor” imagers). ● Limited psychometrically validated and cross-culturally adapted versions available.
Mental chronometry	● Easy to administer. ● Inexpensive measurement.	● Semi-objective measure of the temporal concordance between mental and physical actions. ● No information on psychometric properties of specific paradigms. ● Results are highly task dependent.
Mental rotation tasks	● Objective measure of speed and accuracy. ● Inexpensive measurement.	● Possibility to use different strategies (including non-motor imagery-based approaches). ● Results are highly stimulus

		dependent.
Motion capture	● Objective measure of position and timing. ● High spatial and temporal resolution and fine-grained analysis (e.g. joint angles, trajectories, timing). ● Highly complementary with other techniques (e.g. TMS).	● Relatively expensive equipment. ● Time-consuming and complex analysis.
Eye tracking	● Objective measure of eye position and movement ● High temporal resolution and spatial accuracy (e.g. ‘hotspots’ during action observation). ● Ability to control for head movements.	● Calibration challenges (e.g. sensitive to eye make-up, glasses, etc).
Physiological Procedures		
Autonomous Nervous System Activation (Electrodermal Activity, Cardiac Frequency)	● Objective measures of skin conductance and heart rate. ● Inexpensive measurements. ● Sensitivity to emotional and arousal-related responses. ● High temporal resolution. ● Easily applicable in real-world contexts outside of laboratory settings.	● Inter- and intra-subject variability. ● Influence of environmental factors (e.g. temperature, humidity, medication, etc). ● Indirect measurements of imagery-related neural activity (i.e. limited specificity).
Skin Surface Electromyography	● Objective measure of muscle activity. ● Specific to motor output. ● High temporal resolution.	● Relatively expensive equipment. ● Indirect measurement of imagery-related neural activity. ● Limited to surface muscles. ● Limited to assess action simulation at the execution level.
Transcranial Magnetic Stimulation	● Objective measure of corticospinal excitability. ● Wide variety of procedures possible (measuring response amplitudes, cortico-motor recruitment curves, interactions between different sites, etc).	● Relatively expensive equipment. ● Generally, also requires electromyography to record Motor Evoked Potentials. ● Relatively time-consuming. ● Inter- and intra-subject variability. ● Exclusion criteria due to safety procedures.
Electroncephalography/	● Objective measures of neural oscillatory activity.	● Relatively expensive equipment. ● Time-consuming and complex

Functional Near-Infrared Spectroscopy	High temporal resolution allows examination of different stages of action simulation processing.	administration/analysis. ● Signal noise. ● Limited spatial resolution.
Magnetic Resonance Imaging/Positron Emission Tomography	● Objective measures of blood flow activity. ● High spatial resolution. ● Whole-brain coverage.	● Expensive equipment. ● Physical constraints. ● Complex data analysis. ● Limited temporal resolution.

1.2 General Recommendations: Results

1.2.1 Reporting of Statistics

It is generally recommended that authors provide sample sizes, mean and standard deviation (or standard error of the mean, which allows calculation of the standard deviation based on sample size) for all groups and tests examined in their original work, alongside effect size calculations. This is beneficial not just to the interpretation of the effects presented, but also for their future synthesis (i.e. traditional meta-analytic techniques extract data from the published studies in order to calculate a pooled effect size; Mikolajewicz and Komarova, 2019). Including this information can therefore facilitate the potential future synthesis of original research studies.

1.2.2 Data Sharing and Open Science Practices

Open science initiatives have improved access to raw datasets from published studies. These practices benefit both the authors of the original research and the wider scientific community. Early reports indicate that data sharing increases the visibility of publications, increasing their citations by 25% (Colavizza et al., 2020). Moreover, data sharing opens the exciting possibility to conduct meta-analyses based on raw data from individual participants (sometimes termed “mega-analyses” to help distinguish them from traditional “summary statistic” meta-analyses;

(Eisenhauer, 2021). While direct comparisons have shown that the results of meta- and mega-analysis generally converge, the additional detail available in mega-analysis can allow for greater sensitivity (Eisenhauer, 2021), which has led to the suggestion that mega-analyses represent the “gold standard” for empirical research (Sung et al., 2014; Tierney et al., 2015).

The possibility to conduct future mega-analyses is critically dependent on the ability to access raw data. Because issues such as confidentiality, informed consent, and planned future analyses on the same dataset mean that sharing of raw data is not always possible, open data is not included as a ‘hard’ criterion in the current checklists. We do, however, strongly advocate for data sharing wherever possible. Researchers are advised to include statements in their ethics proposals and informed consent documents that will allow them to share anonymized individual data from their studies. Data can then be uploaded to free repositories such as the Open Science Framework (Foster and Deardorff, 2017). Including a DOI link in the subsequent manuscript makes the data readily accessible.

We also recommend that researchers consider including processing pipelines (i.e. code/scripts used to process the data and output files in a format suitable for analysis) as open resources alongside the raw data. From personal experience, we note that special attention should be paid to ensuring that processing pipelines run to completion on a ‘fresh install’. We also recommend documenting any critical dependencies (e.g. specific versions of software, required toolboxes, etc) that are not included in the resources provided, but are needed for the pipeline to run to completion.

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