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Évaluation et mise en évidence des effets de la charge mentale de travail sur l'adaptabilité comportementale et physiologique

Charlotte Mallat

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THÈSE

En vue de l'obtention du

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Présentée et soutenue par

Charlotte Mallat

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de la charge mentale de travail sur l'adaptabilité
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Résumé

Face à une évolution technologique croissante centrée sur la conception et l'automatisation pour plus de performance, étudier les effets de la charge mentale de travail sur l'efficacité et l'adaptabilité humaine présente un réel intérêt.

L'objectif de ce manuscrit est d'évaluer la charge mentale de travail et de mettre en évidence ses effets sur l'efficacité, se traduisant par une adaptabilité comportementale et physiologique de l'opérateur. Plus précisément, il s'agit de faire varier les exigences de la tâche (par exemple, la difficulté, la pression temporelle, la complexité) pour évaluer et identifier les effets engendrés sur l'adaptabilité de l'opérateur. L'adaptabilité comportementale était indexée à la performance avec la mise en place de stratégie et l'adaptabilité physiologique à la mobilisation de l'effort mental avec le score de réactivité de la période de pré-éjection.

Le premier chapitre démontre un effet curvilinéaire de la charge mentale de travail sur l'adaptabilité comportementale et physiologique, comme postulé par Hancock et Szalma (2006). Le second chapitre met en évidence que la pression temporelle pouvait dans une certaine mesure favoriser l'adaptabilité comportementale, notamment la mise en place de stratégie. Le troisième chapitre montre que les tâches complexes de contrôle du trafic aérien permettent l'activation du compromis performance-effort se traduisant par une adaptabilité comportementale et physiologique de l'opérateur.

Ce manuscrit met en lumière l'importance des facteurs humains dans la boucle de conception des environnements de travail, afin de les repenser et/ou de faire intervenir des outils d'aide si nécessaire, au moment le plus opportun et sous sa forme la plus probante, afin de favoriser une charge mentale optimale.

Mots-clés : Charge mentale de travail, Performance, Effort, Réactivité cardiovasculaire.

Abstract

Faced with a growing technological evolution-oriented design and automation, studying the effects of mental workload on human efficiency and adaptability arouses genuine interest.

The objective of this manuscript is to evaluate the mental workload and to highlight its effects on efficiency, resulting in a behavioral and physiological adaptability of the operator. More precisely, it is a matter of varying the task demand (for example, the difficulty, the temporal pressure, the complexity) to evaluate and identify the effects on the behavioral and physiological adaptability of operator. Behavioral and physiological adaptability was indexed by performance and pre-ejection period reactivity related to effort mobilization.

The first article allowed us to highlight a curvilinear effect of mental workload on behavioral and physiological adaptability, as postulated by Hancock and Szalma (2006). The second article has showed that the temporal pressure could to a certain extent promote behavioral adaptability, especially the implementation of strategy. The third article has demonstrated that the air traffic control complex tasks are likely to activate a performance-effort trade-off resulting both behavioral and physiological adaptability of the operator.

The applicative purpose of this thesis is to highlight the importance of human factors in the environments design loop, in order to rethink them and/or to bring in tools of help if necessary, at the most opportune moment and in its form the most convincing, in order to promote an optimal mental workload.

Keywords: Mental workload, Performance, Effort, Cardiovascular reactivity

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INTRODUCTION GENERALE

Face à une évolution technologique grandissante, orientée vers l'Interaction Homme-Machine (IHM) et l'automatisation, la nature même de l'activité de travail a évolué. L'opérateur est passé d'acteur à superviseur de son activité. Prenons l'exemple du contrôleur aérien. Dans les années 40, le contrôleur aérien utilisait des tables de *plotting* pour illustrer la position des avions dans l'espace aérien, grâce à l'utilisation de données radars relatives à la position des avions pour des besoins militaires. Du fait de l'évolution technologique et de la démocratisation du transport aérien, le déplacement manuel des avions effectué sur la table de plotting s'est automatisé et le résultat affiché sur un écran (Cf. Figure 1). De nos jours, l'image s'actualise toutes les 8 secondes, en fonction des communiqués des radars au sol. L'écran est pourvu des différentes fonctions comme le zoom, le déplacement, le calcul de distance entre avions, etc. De plus, un système de contrôle des séparations, appelé *filet de sauvegarde* (STCA - Short Term Conflict Alert), est intégré à l'image radar. Ce système de protection permet d'alerter le contrôleur par le biais d'une alarme, lorsque des avions risquent de se rapprocher dangereusement dans les minutes qui suivent. D'après le rapport d'activité de la Direction des Services de la Navigation Aérienne de France (DNSA), le nombre de vols par jour a augmenté de 12% entre 2014 et 2018 - avec en moyenne 8830 vols journaliers en 2018. Actuellement, le contrôleur aérien suit jusqu'à 28 avions par heure ; et jusqu'à 15 avions simultanément, à proximité des grands aéroports. Le contrôleur aérien est donc passé d'acteur de son activité en modifiant lui-même le positionnement et le déplacement des avions sur la table de plotting, à superviseur avec de plus en plus d'avions à gérer, principalement à travers un écran muni de divers outils automatisés. L'évolution technologique intarissable et l'impact provoqué sur l'activité de travail, questionnent l'efficacité et l'adaptabilité de l'opérateur face à une charge mentale de travail imposée, de plus en plus importante. L'efficacité se définit par l'atteinte de performance satisfaisante pour un coût mental acceptable (Leplat, 1988). Cela renvoie également au concept proposé par Amalberti (1996) d'un compromis cognitif entre le niveau de performance

suffisant répondant aux exigences de la tâche et le coût cognitif acceptable pour l'opérateur. Maîtriser la situation consiste alors, pour l'opérateur, à gérer ce compromis cognitif. Un déséquilibre dans ce compromis conduirait à une moins bonne performance, ainsi qu'à des perturbations trop coûteuses pour l'opérateur (Csikszentmihalyi, 1991 ; Regan, Victor, & Lee, 2013 ; Young, Brookhuis, Wickens, & Hancock, 2015). Selon Hoc, Amalberti, Cellier et Grosjean (2004), ce compromis cognitif encourage une adaptation continue de l'opérateur. D'après Hancock et Warm (1989), les processus adaptatifs peuvent dans une certaine mesure réguler les effets de la charge mentale de travail imposée, à travers des stratégies de réponse d'un certain nombre de structures corporelles.

Cette thèse articles s'inscrit dans la continuité de ces travaux princeps, car elle a pour objectif de mieux comprendre les effets de la charge mentale de travail sur l'efficacité conduisant à une adaptabilité comportementale et physiologique de l'opérateur. Plus précisément, il s'agit de mettre en évidence les effets des exigences de la tâche (par exemple, la difficulté, la pression temporelle, la complexité) sur l'adaptabilité de l'opérateur, avec la mise en place de stratégies comportementales et la mobilisation plus ou moins importante d'effort mental.

Le deuxième objectif de ce manuscrit est de proposer une approche méthodologique permettant d'évaluer la charge mentale de travail et ses effets sur l'adaptabilité de l'opérateur. Il s'agit de présenter une approche multiple de la mesure, alliant des mesures de performance avec une mesure subjective et une mesure physiologique nous permettant d'avoir des informations complémentaires sur la charge mentale de travail, afin de favoriser l'adaptabilité de l'opérateur pour une charge mentale optimale.

La contribution ergonomique de cette thèse est de mettre en lumière l'importance des facteurs humains dans la boucle de conception des environnements, afin de les repenser et/ou de faire intervenir des outils d'aide si nécessaire, au moment le plus opportun et sous sa forme la plus probante.



1940



2019

Figure 1. Evolution technologique du contrôle aérien, des années 1940 à aujourd'hui.

Ce manuscrit comprend deux parties principales, une partie théorique constituée de deux chapitres et une partie expérimentale organisée autour de trois articles.

Le Chapitre 1 de la partie théorique porte sur le concept central de cette thèse, qui est la charge mentale de travail. Ce chapitre vise à distinguer et à définir les principales dimensions qui composent la charge mentale de travail. Il présente également les modèles d'efficacité traduisant une gestion de la charge mentale de travail traduisant l'adaptabilité de l'opérateur.

Après avoir clarifié le cadre disciplinaire et théorique du concept de charge mentale de travail dans lequel s'inscrit cette thèse, le Chapitre 2 aura pour but de répondre à la question suivante : quelles sont les méthodes disponibles pour évaluer la charge mentale de travail et ses effets ? Pour y répondre, ce chapitre énoncera les différentes mesures de la charge mentale de travail présentes dans la littérature, afin d'en déduire l'approche la plus appropriée à cette thèse.

À la suite de la partie théorique, nous présenterons la problématique de recherche qui encadre la partie expérimentale ainsi que les hypothèses de recherche émanant qui ont été investiguées.

La partie expérimentale est structurée en trois articles s'appuyant sur ce cadre théorique, pour affiner plusieurs hypothèses en situation expérimentale.

Plus précisément, dans le premier article de cette partie, nous avons testé l'effet curvilinéaire de la charge mentale de travail sur l'adaptabilité comportementale et physiologique de l'opérateur observé dans la littérature en ergonomie cognitive (Hancock & Caird, 1993 ; Hancock & Szalma, 2006). Une approche multiple de la mesure a été mise en place pour évaluer la charge mentale de travail. Cette approche est composée d'une mesure subjective, de mesures de performance et d'une mesure physiologique. Afin de pouvoir tester la relation curvilinéaire et notre approche méthodologique, cette expérience s'est déroulée en laboratoire auprès de cent étudiants universitaires, à travers une tâche de pointage sur ordinateur.

Dans le second article, une étude vise à déterminer si la pression temporelle module l'effet curvilinéaire de la charge mentale de travail sur l'adaptabilité comportementale et physiologique.

Dans le troisième article, il s'agit de tester l'effet des paramètres de contrôle du trafic aérien sur le compromis cognitif (une performance satisfaisante pour un coût acceptable) à travers une l'adaptabilité de l'opérateur.

Enfin, pour clore le présent manuscrit, une discussion générale dressera le bilan des différentes implications aussi bien théoriques que méthodologiques, ainsi que les perspectives qui émanent du travail de recherche réalisé.

PARTIE THEORIQUE

CHAPITRE 1. LA CHARGE MENTALE

L'objectif de ce chapitre est de bien préciser le concept de charge mentale, et ce qui le constitue.

Nous présenterons tout d'abord le contexte disciplinaire dans lequel nous nous inscrivons. Toutefois, ce positionnement seul n'évite pas une certaine confusion dans les concepts qui gravitent autour de la charge mentale. Nous allons donc déterminer les points communs des différentes approches et définir la charge mentale et sa composition multidimensionnelle. Après avoir défini la charge mentale et ses dimensions, nous discuterons des six modèles associés aux dimensions choisies. Les modèles seront divisés en deux catégories, les modèles analytiques et les modèles systémiques.

Ce premier chapitre se clôturera par le positionnement théorique de ce travail de thèse.

1.1. UN CONCEPT TOUJOURS D'ACTUALITE

La charge mentale est un concept pluridisciplinaire qui comporte une multitude de points de vue, à travers les disciplines mobilisées. En psychologie expérimentale, la charge mentale est davantage liée au traitement de l'information, aux limites et aux capacités mnésiques (Leplat, 2002). Tandis qu'en ergonomie, le concept de charge mentale fait référence aux sollicitations imposées à l'opérateur (Laville, Teiger, & Duraffourg, 1972). Cette multiplicité disciplinaire a pour conséquence de rendre le concept controversé et d'entraîner des confusions sur les termes employés. Il est important d'avoir conscience du cloisonnement qui existe entre les disciplines mobilisées pour comprendre la définition des concepts et des travaux menés et publiés dans la littérature (Cegarra, 2012).

Plus précisément, une des différences résultant de l'origine disciplinaire concerne les populations cibles des travaux menés : l'Homme, dans le cas de la psychologie expérimentale et l'Homme au travail (opérateur) dans le cas de l'ergonomie. Cette caractéristique justifie que dans la suite de la thèse, la charge mentale soit dénommée « charge mentale de travail » ; et la notion

d'opérateur sera principalement utilisée pour désigner l'Homme au travail. Le terme d'activité de travail quant à lui, concernera la réalisation de la tâche par l'opérateur.

Etudier la charge mentale de travail de l'opérateur présente un enjeu majeur en ergonomie cognitive (Chanquoy, Tricot, & Sweller, 2007 ; Martin, Hourlier, & Cegarra, 2013 ; Tort, 1976 ; Young et al., 2015). Elle permet d'obtenir des informations capitales sur les déterminants des modes opératoires des opérateurs, ainsi que sur la qualité des interactions entre l'opérateur et les outils utilisés dans l'exécution de la tâche (Loft, Sanderson, Neal, & Mooij, 2007).

De plus, la charge mentale de travail est un concept ancien qui a beaucoup évolué, pour donner suite à l'arrivée de nouveaux objets d'étude. L'usage de la charge mentale de travail s'est véritablement établi dans le domaine de l'ergonomie au cours des années 1970-80, avec la publication de textes majeurs sur le sujet (Meshkati, 1988 ; Moray et al., 1979). Initialement, l'accent était plutôt mis sur la dimension méthodologique (Hart & Staveland, 1988 ; Leplat & Pailhous, 1969), puis sur la modélisation du concept (par exemple, Hancock et Chignell, 1988), en élargissant progressivement ses nombreux domaines d'application à l'aéronautique ou l'automobile (Béquet, Astier-Juvenon, Pépin, Gabaude, & Hidalgo-Muñoz, 2018 ; Masaloni, Duley, & Parasuraman, 1999 ; Stanton & Young, 1998 ; Svensson, 1997 ; Young et al., 2015 ; Young & Stanton, 2004).

1.2. L'ETUDE DE LA CHARGE MENTALE : DEFINITIONS

Il existe de nombreuses définitions de la charge mentale de travail, que nous proposons ici de confronter à travers cinq définitions principales soulignant toute la richesse contenue dans ce vocable.

Leplat (1977) définit la charge mentale de travail comme les ressources cognitives mobilisées par l'opérateur face aux exigences de la tâche qu'il réalise. Cette définition présente la charge mentale de travail comme un produit de l'interaction entre l'homme et la tâche. Elle montre

également que l'opérateur est perçu comme un acteur face à la charge mentale de travail qu'il rencontre (Spérando, 1977).

La charge mentale est également considérée comme une construction multidimensionnelle. Meshkati (1988, p.309) décrit la charge mentale de travail comme « reflétant l'interaction d'éléments tels que les exigences de la tâche, le système, les capacités de traitement, l'effort de l'opérateur, les critères de performance subjectifs, le comportement de traitement de l'information, les stratégies de l'opérateur et la formation ainsi que l'expérience antérieure des opérateurs ». Meshkati (1988) met donc en avant une multitude de dimensions composant la charge mentale de travail.

Renforçant encore l'aspect multidimensionnel de la charge mentale de travail, la norme internationale (ISO 10075) s'est, elle aussi, articulée autour de deux dimensions centrales : le stress et l'effort (ISO 10075, 2000). Le stress faisant référence aux exigences liées à la tâche ; et l'effort, aux ressources déployées par l'opérateur. Ces deux dimensions sont elles-mêmes associées à de multiples facteurs. Dans cette approche, on considère donc la charge mentale de travail en termes d'équilibre entre exigences et ressources (Hancock & Warm, 1989).

De plus, Wickens et Hollands (2000) définissent la charge mentale de travail en termes de relation entre la demande (exigences) et l'offre (ressources disponibles). Cette approche met l'accent sur les variations de charge mentale de travail ressentie par l'opérateur au cours de l'exécution de la tâche. En effet, l'opérateur s'adapte au niveau des exigences de la tâche à réaliser, à travers l'objectif fixé.

La cinquième définition est proposée par Hart et Staveland (1988). Ils définissent la charge mentale de travail comme l'interaction entre les exigences de la tâche, l'opérateur et l'environnement. Dans cette approche, la charge mentale de travail est alors un construit hypothétique, représentant pour un humain le coût d'accomplissement de la tâche (demande/ressources) avec un certain niveau de performance. Cette représentation du concept de charge mentale de travail met également en exergue la place centrale occupée par la performance dans la détermination du niveau de charge mentale de travail. En outre, l'approche de Hart et

Staveland associe à la notion de charge mentale de travail une certaine instabilité, liée à des différences dans la gestion des ressources cognitives. En effet, au cours de l'exécution de la tâche, l'état dans lequel se trouve l'opérateur varie selon le niveau de ressources cognitives dans lequel il estime se trouver (voir également De Jong, 2001).

Ces différentes définitions reliées à la charge mentale de travail ont permis de mettre en évidence des caractéristiques communes centrales telles que les exigences de la tâche liées à la demande (approche externe), l'effort mental mobilisé face à ces exigences (approche interne dépendante de l'opérateur) et la performance à maintenir à un certain niveau, selon l'objectif fixé. Ces trois dimensions composent et font varier le niveau de charge mentale de travail. Nous allons maintenant les décrire plus précisément.

1.3. LES DIMENSIONS THEORIQUES ASSOCIEES

1.3.1. Les exigences de la tâche

Les exigences de la tâche relèvent d'une approche externe de la charge mentale de travail. Elles ne prennent pas en compte les caractéristiques de l'opérateur : il s'agit bien d'exigences imposées à celui-ci. Elles peuvent être constituées de différents facteurs. Dans leur étude sur la relation entre les exigences de la tâche et l'adaptabilité, Hancock et Warm (1989) ont proposé deux facteurs fondamentaux, selon lesquels les tâches varient. Ces deux facteurs sont le taux d'information présenté faisant référence à la pression temporelle, et la structure de l'information (notamment, la difficulté de résolution du problème).

Ainsi, la pression temporelle implique-t-elle un conflit entre le temps disponible pour effectuer une tâche et la durée réelle de la tâche (Rastegary & Landy, 1993). Les contraintes de temps imposant souvent un stress et une charge mentale de travail considérables aux opérateurs (Szalma, 2008).

La difficulté peut être définie comme une inadéquation entre la représentation interne de l'opérateur et le problème à résoudre (Cegarra, 2012). La difficulté d'une tâche reste liée notamment au traitement requis par l'opérateur pour l'exécution (De Waard, 1996). La difficulté peut dépendre du contexte, de l'état, de la capacité ou de la stratégie d'allocation des ressources.

Il existe une certaine confusion entre la difficulté et la complexité d'une tâche (Liu & Li, 2012). La complexité fait référence au nombre de variables à contrôler pour effectuer une tâche (Funke, 2001 ; Hoc, 1991 ; Leplat, 1988). Plus le nombre de variables à contrôler est important et plus elles interagissent entre elles, plus la tâche est complexe.

Ces trois facteurs, qui composent les exigences de la tâche présentées, se retrouvent dans de nombreuses situations de travail. Par exemple, dans des travaux en aéronautique (Wickens, 2002) ; dans le transport ferroviaire (Pickup et al., 2010) ou encore la conduite automobile (Young et Stanton, 2004).

Pour répondre à ces exigences imposées par la tâche, l'opérateur mobilise de l'énergie, qui est nommée effort mental.

1.3.2. L'effort mental

L'effort mental désigne la composante interne, énergétique de la charge mentale de travail. L'effort mental est défini comme la quantité de ressources mobilisées par l'opérateur dans la réalisation d'une tâche (Kahneman, 1973). Hockey (1997) considère, quant à lui, l'effort mental comme la stratégie compensatoire visant à protéger la performance, lorsque les exigences de la tâche augmentent. L'effort mental est donc la quantité réelle de mobilisation cognitive fournie par l'individu (Matthews, Warm, Reinerman-Jones, Langheim, Washburn, & Tripp, 2010 ; Paas & Van Merriënboer, 1993). C'est une dimension centrale de la charge mentale de travail qui reflète la réaction physiologique de l'opérateur aux exigences de la tâche. Selon Mulder (1986) et Kahneman

(1973), l'effort mental peut être observé de manière objective à travers différents indicateurs physiologiques.

L'effort mobilisé peut dépendre des caractéristiques de la tâche, de la pratique, de l'expérience ainsi que de l'état de l'opérateur. Selon la *théorie du contrôle d'état* (Hockey, 1986), les mécanismes exécutifs centraux comparent l'état cognitif actuel à un état cible. Lorsqu'il existe une inadéquation entre ces deux états, l'effort peut être mobilisé dans la manipulation active de l'état actuel vers l'état cible. Hockey (1986) appelle cette régulation la « gestion d'état » (state control). En mobilisant de l'effort mental, il est possible de limiter les influences néfastes des facteurs tels que la surcharge d'information ou la sous-sollicitation. Une tâche de nature ennuyeuse du fait de sa sous-sollicitation peut par exemple, stimuler un effort mental compensatoire pour maintenir un niveau de performance acceptable.

L'effort mental se distingue toutefois de l'éveil ou de l'activation. En effet, l'effort mental représente une forme d'activation dédiée à l'exécution d'une tâche, alors que l'activation est plutôt une excitation globale du corps (provoquée par exemple par la joie, la colère). L'éveil et l'activation induisent des états transitoires, dont nous pouvons mesurer le niveau en dehors de toute tâche. En comparaison, l'effort mental est un mécanisme énergétique coordinateur, qui mobilise des ressources vers un objectif fixé lors de l'accomplissement d'une tâche (Sanders, 1983).

1.3.3. Les ressources de l'opérateur

Les ressources mobilisées lors de l'effort mental font souvent référence aux ressources attentionnelles (Hancock & Warm, 1989 ; Wickens, 1980, 2002, 2017 ; Young et al., 2015 ; Young & Stanton, 2002). Ainsi, la charge mentale de travail devient le produit des ressources disponibles pour répondre aux exigences de la tâche (Welford, 1978). Les ressources y constituent une quantité de « carburant » utilisée par le « moteur cognitif » pour l'exécution d'une tâche. La mobilisation des ressources génère donc un coût, appelé coût cognitif, qui correspond à la part nécessaire d'effort à

mobiliser pour réaliser une tâche. Elles représentent la façon dont l'opérateur va percevoir le niveau d'exigence de la tâche et dont il va y répondre (voir aussi Sweller et al., 1990). La mobilisation des ressources est donc un processus volontaire et dynamique à l'initiative de l'opérateur (Hancock & Warm, 1989 ; Hockey, 1997 ; Kahneman, 1973).

Toutefois, les ressources attentionnelles disponibles possèdent une capacité limitée. Au-delà de cette limite, les exigences de la tâche se manifestent par une dégradation des performances, puis un désengagement. Le concept de capacité de traitement limitée peut être souligné dans de nombreuses théories (par exemple : Broadbent, 1958 ; Kahneman, 1973 ; Posner, 1978 ; Wickens, 1984). Kahneman (1973) décrit une théorie de ressources unitaires, limitées et divisibles. Cela signifie que plusieurs processus peuvent bénéficier d'un même ensemble de ressources simultanément susceptibles de varier, selon les exigences de la tâche. Des études anciennes telles que celle réalisée par O'Donnell et Eggemeier (1986) ne distinguent pas les concepts de « capacité » et de « ressources » et les utilisent de façon interchangeable. Cependant, Wickens (1992) définit la capacité comme la limite maximale de traitement, tandis que les ressources représentent l'effort mental fourni pour améliorer l'efficacité du traitement. Autrement dit, la capacité correspond à la quantité maximale de ressources que peut mobiliser l'opérateur pour répondre à une tâche.

La notion de ressource représente donc plus précisément « l'énergie mentale disponible pour un individu particulier, à un instant donné et pour un traitement particulier » (Chanquoy et al., 2007). Le recours aux ressources nécessite une modulation de l'énergie déployée par l'opérateur, traduisant un effort mental. Cette modulation traduit une adaptabilité physiologique de l'opérateur face aux exigences de la tâche.

La mobilisation de l'effort mental et plus particulièrement des ressources, constitue ainsi une réponse énergétique de l'opérateur face aux exigences de la tâche. Par ailleurs, le niveau de performance atteint est une réponse comportementale de l'opérateur face aux exigences.

1.3.4. La performance

La performance permet d'évaluer l'atteinte des objectifs associés aux exigences de la tâche (Delignières, 2004). La performance peut effectivement être évaluée par le biais d'indicateurs de performance comme le taux d'erreur, le temps de réaction, etc. Il est essentiel de noter que les indicateurs de performance sont propres à chaque tâche (Bayssie & Chaudron, 2002).

Les critères de performance peuvent être prescrits, ou peuvent désigner ceux que se fixe l'opérateur (Hancock & Caird, 1993). De plus, lors de l'exécution d'une tâche, nous pouvons distinguer deux types de performance : la première est l'objectif fixé par l'opérateur qui symbolise un résultat attendu, la performance visée. La seconde est le résultat obtenu une fois la tâche effectuée. Cette distinction est importante, car elle peut modifier le comportement et les stratégies mises en place par l'opérateur.

Lorsque les exigences de la tâche augmentent face aux ressources disponibles, cela crée un déséquilibre dans la balance entre exigences et ressources, en altérant la performance. Face à ce déséquilibre, l'opérateur va mettre en place jusqu'à un certain niveau des processus adaptatifs pour maintenir, préserver la performance (Hancock & Szalma, 2006 ; Hockey, 1997 ; Kahneman, 1973). Les processus adaptatifs ou compensatoires dépendent des stratégies de réponse d'un certain nombre de structures corporelles qui régulent les effets de la demande de tâches (Hancock & Warm, 1989). Par exemple, il est très fréquent dans des tâches de laboratoire, d'observer un compromis entre vitesse et précision. Dans ces tâches-là, comme la tâche de Fitts, l'opérateur doit se montrer plus rapide et moins précis, pour garantir un certain niveau de performance face aux exigences de la tâche (Hancock, Chignell, & Kerr, 1988 ; Hoffmann, 2011; Hoffmann, Chan, & Dizmen, 2013 ; Plamondon & Alimi, 1997 ; Rozand, Lebon, Papaxanthis, & Lepers, 2015).

Lorsque les adaptations ne sont pas, ou plus efficaces, deux phénomènes peuvent être constatés, la sous-charge et la surcharge. La sous-charge est définie par une faible sollicitation par rapport aux ressources disponibles. Inversement, la surcharge est définie par des exigences trop

importantes par rapport aux ressources disponibles (Brookhuis, De Waard, & Fairclough, 2003 ; Hancock, 2013 ; Young et al., 2015) Les deux phénomènes pouvant entraîner une dégradation des performances, ainsi que des défaillances de l'attention et des erreurs (Wilson & Rajan, 1995).

Après avoir clarifié le concept de charge mentale de travail et les dimensions théoriques associées, nous traiterons des modèles théoriques reprenant ces dimensions.

1.4. LES MODELES ASSOCIES A CES DIMENSIONS

Les modèles présentés ici sont des modèles d'efficience qui visent une charge mentale de travail optimale, avec l'atteinte de performances satisfaisantes pour un coût acceptable, grâce à l'adaptabilité de l'opérateur. Nous aborderons tout d'abord les modèles analytiques en ergonomie cognitive ayant comme dimensions, les exigences de la tâche (à travers divers facteurs) et la performance de l'opérateur. De plus, deux modèles analytiques issus de la psychologie expérimentale, directement liés à l'état physiologique de l'opérateur seront présentés. Ces modèles traitent de l'effort mental, la performance, ou encore les exigences de la tâche. Enfin, nous aborderons les modèles systémiques, mettant en relation l'ensemble des dimensions théoriques associées à la charge mentale de travail énoncées dans cette thèse.

1.4.1. Les modèles analytiques

1.4.1.1. Yerkes et Dodson (1908) : stress et performance

Yerkes et Dodson (1908) ont formulé leur loi pour tenir compte de la variance dans la formation des habitudes, basée sur la force des stimuli utilisés dans les paradigmes de conditionnement. Lorsque les stimuli étaient soit trop intenses, soit manquant d'intensité, il y avait une baisse de performance. D'après Klein (1982), la fonction de Hebb (1955) fait évoluer

l'illustration de la loi de Yerkes et Dodson (1908) à travers une courbe curvilinéaire à deux dimensions distinctes : le stress (exigences de la tâche) et la performance (Figure 2). La partie ascendante du U inversé peut être considérée comme l'effet optimal du stress. La partie descendante est causée par les effets néfastes du stress sur les processus cognitifs, tels que l'attention. Plus précisément, le niveau bas de stress est principalement associé au sommeil, à la fatigue ou à un manque de motivation. En son centre, le niveau optimal désigne une performance optimale. Cependant, un niveau de stress élevé est souvent associé à la peur, la panique, l'épuisement et à une concentration plus basse (Thom, Kang, Fisher, & Ischiropoulos, 1997). Lorsque le niveau de stress augmente au-delà du niveau optimal, les performances élevées se détériorent et l'opérateur commet des erreurs.

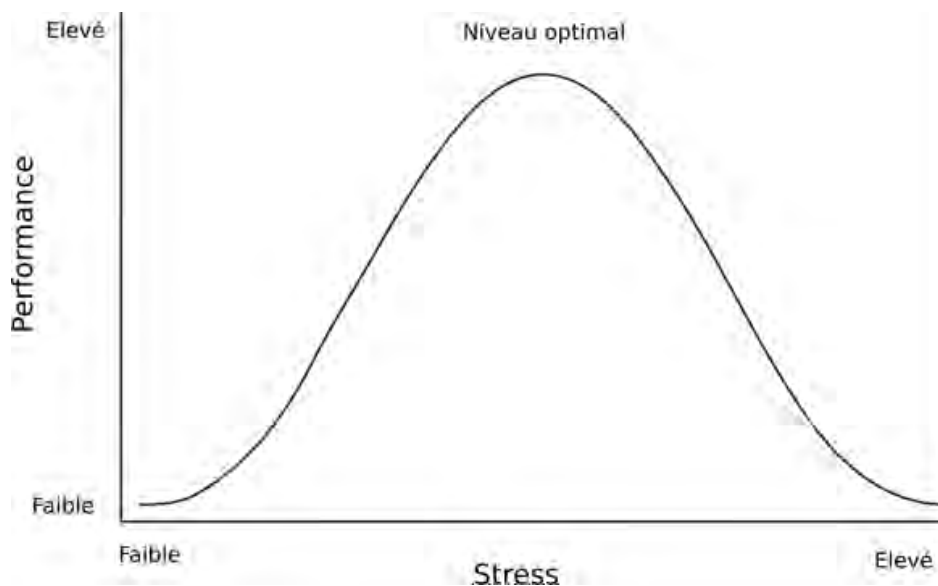


Figure 2. Illustration du modèle curvilinéaire entre le stress et la performance, de Hebb/Yerkes-Dodson Source : Klein, S. B. (1982). *Motivation: biosocial approaches* (p.126) - McGraw-Hill College.

1.4.1.2. Hancock et Chignell (1988) : pression temporelle et objectif visé

Hancock et Chignell (1988) considèrent que l'opérateur peut, à tout moment, être considéré comme évoluant entre le temps restant pour agir et l'avancement dans la résolution de la tâche

(Figure 3). Ces auteurs postulent que la charge mentale de travail va augmenter lorsque l'opérateur s'approche de la résolution de la tâche (sa fin). De plus, ils considèrent que la charge mentale de travail va croître si le temps disponible se réduit (pression temporelle). Plus précisément, lorsque l'opérateur est au début de la tâche et qu'il dispose d'un temps important pour agir, il se trouve dans une zone où la charge mentale de travail est faible à modérée (zone bleue, jusqu'au violet). Inversement, lorsque le temps disponible est insuffisant et que l'opérateur approche de la fin de la tâche, la charge mentale de travail est la plus élevée (zone rose, jusqu'au rouge).

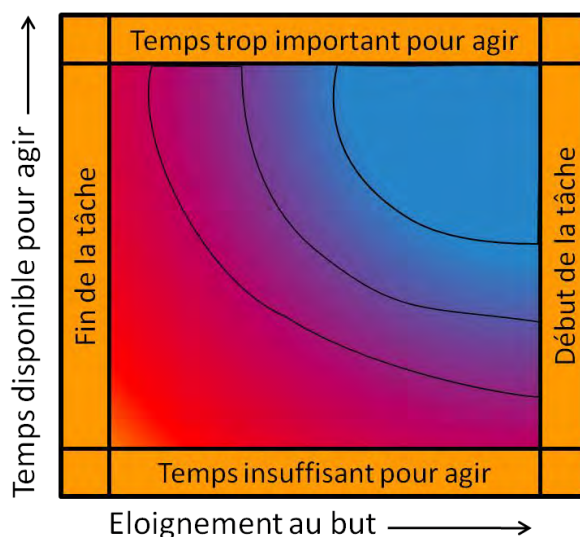


Figure 3. Modèle illustrant les différentes zones de charge mentale selon la pression temporelle, proposé par Hancock et Chignell (1988).

Hancock et Caird (1993) ont ultérieurement proposé une évolution du modèle précédent, en insistant sur le caractère adaptatif de l'opérateur. Les auteurs postulent une relation curvilinéaire de la gestion de la charge mentale de travail (Figure 4). Pour l'opérateur, il existerait une zone de confort (zone violette). Dans cette zone, l'opérateur disposerait de possibilités d'action optimales. En effet, la charge mentale de travail y est optimale pour la réalisation de la tâche, avec un éloignement du but contrôlé et un temps suffisant pour agir.

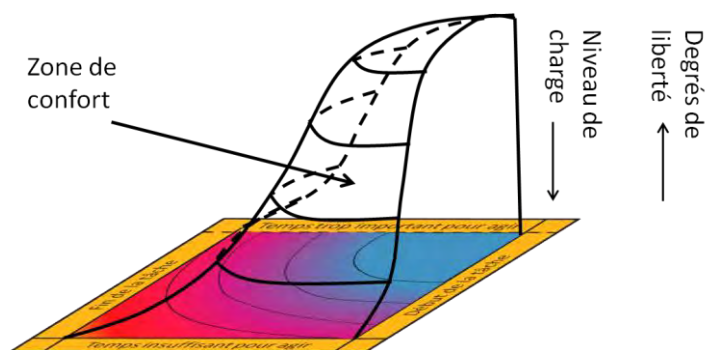


Figure 4. Modèle curvilinéaire de gestion de la charge mentale, proposé par Hancock et Caird (1993).

1.4.1.3. Gardner (1990) : **niveau d'activation et performance**

Gardner (1990) postule, quant à lui, une relation curvilinéaire entre le niveau d'activation lié à la complexité de la tâche et la performance (Figure 5). Le niveau d'activation est défini comme une fonction monotone de la stimulation totale, qui résulte de l'exécution d'une tâche ayant un impact sur une personne à un moment donné. Plus la tâche est complexe, plus les voies sensorielles sont stimulées, et donc plus le niveau d'activation sera élevé. Un niveau d'activation modéré entraîne une performance maximale à la tâche. Le niveau modéré est associé à une utilisation optimale de la mémoire à court terme et à un transfert soutenu d'informations en mémoire (Humphreys & Revelle, 1984). De nombreuses études utilisant ce modèle curvilinéaire s'intéressent aux conditions contextuelles (stress, pression temporelle) qui influencent la créativité au travail (Amabile, 2018 ; Baer, & Oldham, 2006 ; Binnewies, & Wörnlein, 2011 ; Byron, Khazanchi, & Nazarian, 2010 ; Shalley, Zhou et Oldham, 2004). Les auteurs trouvent une relation curvilinéaire entre le stress et la créativité. Plus spécifiquement, alors que le niveau de stress était bas, la créativité augmentait mais lorsque le stress était trop élevé, il semblait entraver de manière significative la créativité.

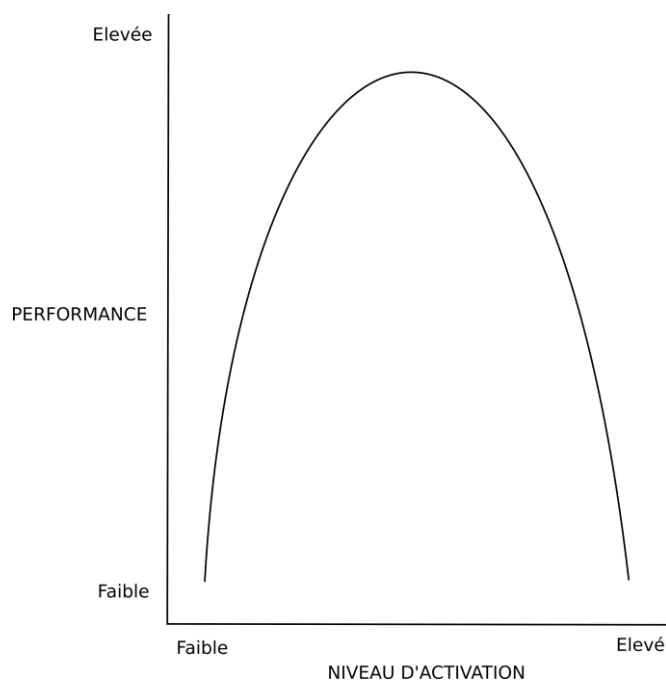


Figure 5. Relation curvilinéaire entre le niveau d'activation et la performance, postulée par Gardner (1990).

1.4.1.4. Brehm et Self (1989) : difficulté perçue et effort mental

La *théorie de l'intensité de la motivation*, de Brehm et Self (1989) postule une fonction linéaire entre la mobilisation de l'effort mental et la difficulté perçue dans la réalisation d'une tâche (Figure 6). La motivation potentielle symbolise la limite supérieure de l'effort consenti par un participant dans l'atteinte des objectifs de la tâche. Si la mobilisation potentielle est basse, alors le participant ne mobilise pas beaucoup d'effort quelque soit le niveau de difficulté. Si la motivation potentielle est haute alors le participant mobilise de l'effort selon la difficulté perçue. De plus, lorsque le participant perçoit la difficulté de la tâche comme impossible à surmonter (c'est à dire au-delà de ses capacités), alors il se désengage de la tâche et ne mobilise plus d'effort. Plus la difficulté perçue de la tâche est élevée, plus le participant mobilise d'effort mental jusqu'à un certain niveau consentie. De nombreuses études ont utilisé la théorie pour aborder divers phénomènes liés à l'effort, tels que l'impact de la capacité, de l'affect et de la fatigue sur la mobilisation de l'effort (Gendolla & Silvestrini, 2011 ; Richter, Gendolla, & Wright, 2016 ; Wright & Kirby, 2001 ; Wright & Stewart, 2012).

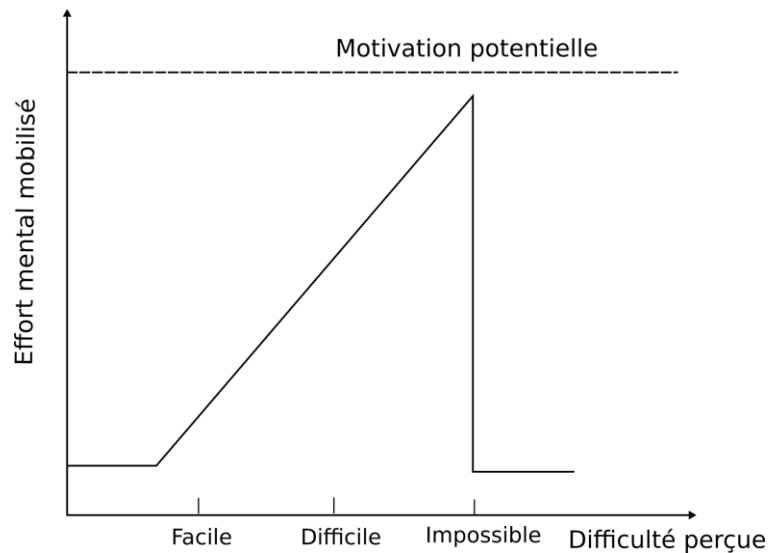


Figure 6. Modèle linéaire entre la difficulté perçue et l'effort mental mobilisé, proposé par Brehm et Self (1989).

1.4.2. Les modèles systémiques

1.4.2.1. Wickens et Hollands (2000) : sollicitation, ressources et performance

À travers cette relation entre sollicitation, ressources mobilisées et performance, Wickens et Hollands (2000) postulent une relation entre deux « zones » de sollicitation faisant toutes deux référence aux exigences de la tâche (Figure 7). Dans la première zone les exigences sont inférieures aux ressources disponibles et la performance est à son maximum. Dans la deuxième zone, les exigences dépassent les ressources disponibles et les capacités de l'opérateur, les performances diminuent jusqu'au désengagement. Par exemple, lorsque les participants réalisent une tâche de plus en plus complexe, la performance (temps, nombre d'erreurs) va progressivement diminuer lorsque les ressources nécessaires seront supérieures aux ressources disponibles.

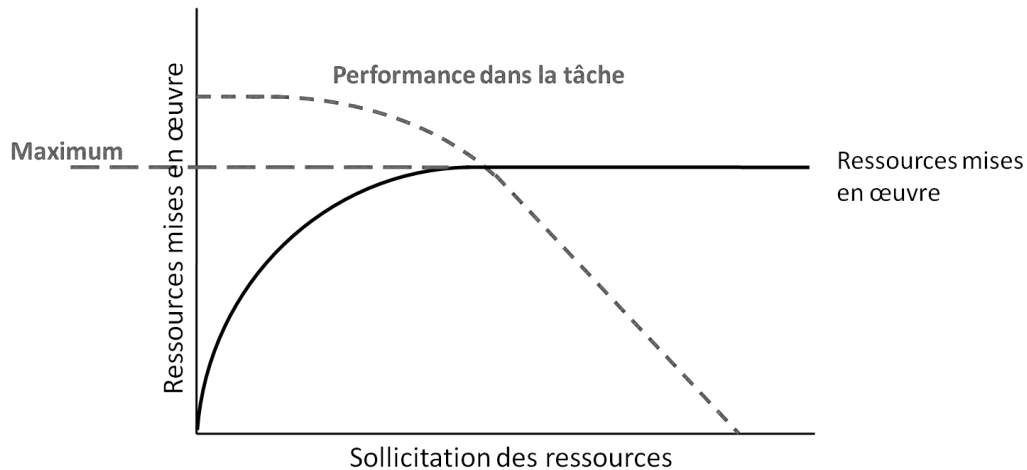


Figure 7. Relation entre sollicitation, ressources mobilisées et performance, postulée par Wickens et Hollands (2000).

1.4.2.2. Hancock et Szalma (2006) : charge mentale de travail et adaptabilité comportementale, physiologique

Précédemment, les modèles d'Hancock et collaborateurs (Hancock & Caird, 1993 ; Hancock & Chignell, 1988) liés aux exigences de la tâche et considérant la pression temporelle, ont été abordés. Les auteurs ont développé différentes zones de charge mentale de travail, selon l'éloignement du but et le temps disponible pour agir. Hancock et Caird (1993) postulent une zone de confort traduisant une charge mentale de travail optimale pour la réalisation de la tâche. Toutefois ces modèles, non systémiques, ne représentent qu'une partie des dimensions associées à la charge mentale de travail.

Quelques années plus tard et dans la continuité, Hancock et Szalma (2006) décrivent un modèle holistique reprenant les trois dimensions principales de la charge mentale de travail : les exigences de la tâche, l'effort mental et la performance. Hancock et Szalma (2006) postulent une relation curvilinéaire du stress et de l'adaptabilité comportementale et physiologique (Figure 8). Hancock et Szalma (2006) considèrent que pour les opérateurs, ce sont les exigences de la tâche qui constituent les principales sources de stress. Les exigences de la tâche peuvent varier d'un niveau extrêmement faible à un niveau extrêmement élevé. C'est-à-dire, entraînant un

« hypostress » pour des exigences très faibles et un « hyperstress » pour des exigences très élevées. Ils font ainsi référence à des situations de sous-charge et de surcharge. Selon les exigences de la tâche, l'opérateur va s'adapter en modulant sa mobilisation d'effort mental (adaptabilité physiologique) et sa performance (adaptabilité comportementale) dans la réalisation de la tâche. Lorsque les exigences de la tâche sont en sous-charge, l'adaptabilité comportementale et physiologique est faible. Cependant, l'adaptabilité comportementale et physiologique augmentera proportionnellement, jusqu'à un niveau intermédiaire. Ainsi, du niveau le plus faible au niveau intermédiaire, une augmentation de l'adaptabilité comportementale et physiologique relève d'un mécanisme compensatoire destiné à protéger la performance ou à ralentir la baisse de la performance. Toutefois, au niveau intermédiaire des exigences de la tâche, l'adaptabilité comportementale et physiologique reste stable et les opérateurs se trouvent dans une zone de confort offrant une adaptabilité maximale. Si les exigences de la tâche progressent vers une surcharge, le niveau d'adaptabilité comportementale et physiologique diminue et la performance décline potentiellement, jusqu'au désengagement.

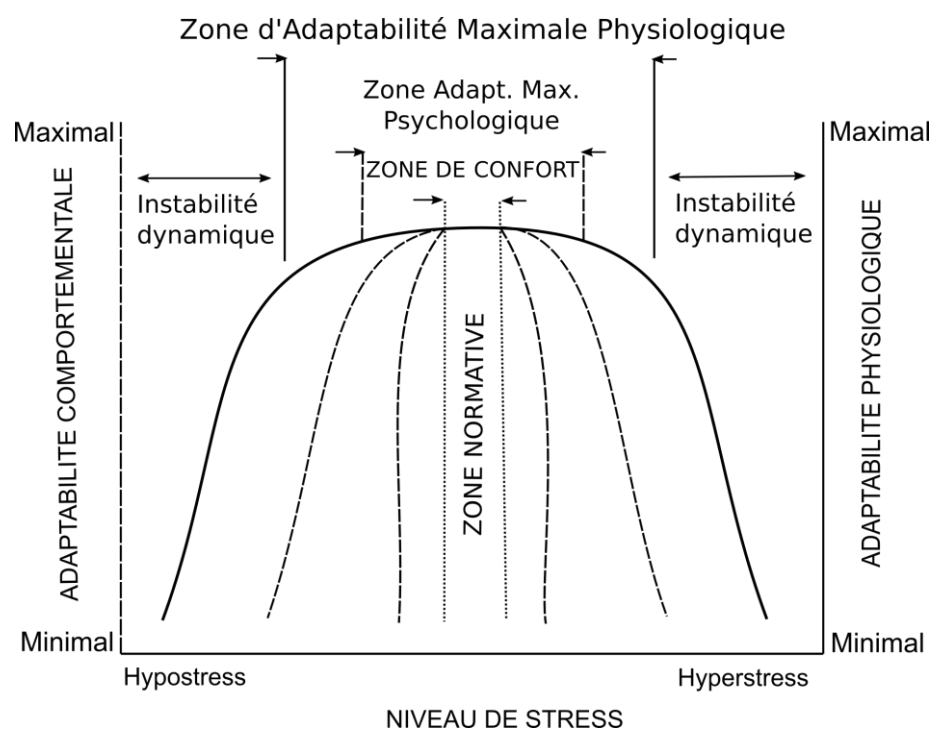


Figure 8. Modèle curvilinéaire de l'effet du niveau de stress sur l'adaptabilité comportementale et physiologique, par Hancock et Szalma (2006).

1.5. CONCLUSION INTERMEDIARE

Le concept de charge mentale de travail est ancien et pluridisciplinaire, en ergonomie. Les recherches sur le concept de charge mentale de travail en ergonomie ont quadruplé depuis 1970, et la multiplicité des domaines d'application montre qu'il est toujours d'actualité. Toutefois, la pluridisciplinarité du concept peut le rendre confus et difficile à définir.

Dans le cadre de cette thèse, nous nous sommes positionnés sur une définition multidimensionnelle, proposée par Hart et Staveland (1988). Cette définition intègre les notions d'exigences de la tâche, d'opérateur comme acteur qui mobilise de l'effort mental, dans un environnement lui demandant une certaine performance lors de la réalisation d'une tâche. Les exigences de la tâche, l'effort mental et la performance sont les trois dimensions principales qui composent et font varier le niveau de charge mentale du travail.

Plus précisément, les exigences de la tâche font référence à une approche multifactorielle externe imposée à l'opérateur comme la difficulté, la pression temporelle, la complexité de la tâche. L'effort mental fait mention de l'approche interne, dépendante de l'opérateur. Il s'agit des ressources cognitives (attentionnelles) mobilisées de façon dynamique et volontaire par l'opérateur. La performance est la composante comportementale qui désigne l'atteinte de l'objectif visé, traduisant une adaptabilité de l'opérateur selon le niveau d'exigences et de ressources.

En accord avec notre choix de définition multidimensionnelle, le modèle systémique d'Hancock et Szalma (2006) articule les trois dimensions de la charge mentale de travail énoncées par Hart et Staveland (1988). Les auteurs postulent un effet curvilinéaire de la charge mentale de travail sur l'adaptabilité comportementale et physiologique. Seulement, leur modèle n'a pas reçu de validation expérimentale globale. Nous pouvons donc nous demander : quels sont les effets de la charge mentale de travail sur l'efficacité, notamment l'adaptabilité de l'opérateur ?

Pour résoudre cette problématique de recherche, nous devons nous poser une seconde question : Quelles sont les méthodes qui permettent d'évaluer la charge mentale de travail et ses

effets ? Le chapitre suivant présentera les méthodes de mesure de la charge mentale de travail, afin d'en déduire l'approche la plus adaptée à ce travail de thèse tout en restant en cohérence avec les situations de terrain associées.

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CHAPITRE 2.
**LES MESURES DE LA CHARGE
MENTALE**

Après avoir clarifié le concept de charge mentale de travail selon une approche multidimensionnelle, dans ce chapitre nous traiterons des mesures de la charge mentale de travail.

O'Donnell et Eggemeier (1986) définissent trois groupes de mesures de la charge mentale de travail : les mesures subjectives des exigences de la tâche, les mesures physiologiques de l'effort mental et les mesures de performance.

L'objectif de ce deuxième chapitre est de décrire chacune des mesures, leurs avantages et inconvénients. Nous développerons ensuite l'intérêt d'une mesure multiple de la charge mentale de travail.

En conclusion, nous présenterons nos choix afin de tester nos hypothèses.

2.1. MESURES SUBJECTIVES DES EXIGENCES

Les mesures subjectives font référence aux exigences de la charge mentale de travail ressenties par l'opérateur. Pour mesurer les exigences de la tâche ressenties par l'opérateur, il convient de nous demander quel outil utiliser. Nous pouvons compter trois outils différents : les entretiens, les questionnaires et les échelles. Dans la littérature en ergonomie cognitive, les échelles sont fréquemment utilisées pour quantifier le niveau moyen de charge mentale de travail ressenti. Parmi les échelles multidimensionnelles les plus fréquemment utilisées, nous retrouvons le NASA-Task Load Index (TLX : Hart & Staveland, 1988) et la Subjective Workload Assessment Technique (SWAT : Reid, Eggemeier, & Shingledecker, 1982). D'autres échelles peuvent également être utilisées pour mesurer des sous-dimensions de la charge mentale de travail. C'est le cas du Dundee Stress State Questionnaire (DSSQ : Helton, Matthews, & Warm, 2009), qui vise à distinguer l'engagement, la détresse et l'inquiétude. De plus, des échelles unidimensionnelles peuvent être utilisées, permettant d'augmenter la précision (sensibilité) sur une dimension en particulier de la charge mentale de travail (De Waard, 1996 ; Hendy, Hamilton, & Landry, 1993). Par exemple, la version française de l'échelle d'Eccles et Wigfield (1995) évalue la difficulté perçue. Cette échelle

montre de bonnes propriétés psychométriques, ainsi qu'une bonne sensibilité aux différences de niveau de difficulté (Capa, Audiffren, & Ragot, 2008). Ou encore l'échelle Modified Cooper Harper (MCH : Wierwille & Casali, 1983), qui est une échelle d'évaluation à une dimension, fondée sur un arbre de décision. Elle a été développée pour des tâches psychomotrices, afin d'évaluer la maniabilité et le contrôle des aéronefs (Cooper & Harper, 1969 ; voir aussi Lysaght, Hill, Dick, Plamondon, & Linton, 1989).

Les échelles unidimensionnelles présentent l'avantage de réduire les biais d'interprétation et d'incompréhension dans l'évaluation subjective de la charge mentale de travail des participants. En outre, Hendy, Hamilton et Landry (1993) ont noté que d'une manière générale, une échelle unidimensionnelle peut prédire une charge globale tout comme une échelle multidimensionnelle. Au fil des ans, différents chercheurs ont cherché à réduire la complexité de ces échelles et leur temps d'évaluation, afin d'en améliorer la validité et la précision (Young et al., 2015).

Dans le cas d'une approche subjective, l'un des choix à prendre porte sur le moment où l'évaluation doit être effectuée. Une évaluation post-tâche, réalisée à l'issue de la tâche expérimentale, est la plus fréquente dans le cadre de l'évaluation subjective de la charge mentale de travail (Young et al., 2015 ; Zijlstra, 1993). Une évaluation au cours de la réalisation de la tâche permet d'inclure la variation de la charge mentale de travail au cours du temps. Toutefois, une telle approche peut être potentiellement intrusive en interrompant la tâche.

Un des grands avantages des mesures subjectives est la haute diagnosticité qu'elles peuvent atteindre (Cain, 2007). La diagnosticité d'une mesure se définit comme permettant de discriminer une hypothèse de ses alternatives (Matthews, Reinerman-Jones, Barber, & Abich, 2015 ; Trope & Mackie, 1987). Plus précisément pour la charge mentale de travail, la diagnosticité est la capacité de discerner le type ou la source de charge, ou encore la capacité à l'attribuer à un aspect ou des aspects de la tâche de l'opérateur (Wierwille & Eggemeier, 1993).

Ce type de mesure subjective bénéficie également d'une très grande facilité d'implémentation et à faible coût. Ainsi, les mesures subjectives peuvent être évaluées même en

l'absence d'action physique, contrairement aux mesures comportementales. De plus, il est possible d'élaborer des questionnaires qui ne soient pas spécifiques à une tâche en particulier. Cet avantage permet de comparer facilement les tâches entre elles.

Les mesures subjectives présentent toutefois quelques limites. D'une part, elles se confrontent aux différences intra et interindividuelles des opérateurs quant à la charge mentale de travail qu'ils ressentent et qu'ils évaluent. D'autre part, elles sont reconnues comme affectées par de nombreux biais cognitifs (par exemple, la sensibilité de la mémoire dans l'estimation et la restitution de la charge mentale ressentie).

2.2. MESURES DE PERFORMANCE

Les mesures de performance ont pour principe d'évaluer la qualité des actions réalisées par l'opérateur. Il s'agit de mesurer les variations de performance à travers différents indicateurs (réussite ou échec des objectifs, durée de réalisation des tâches, etc.) La détermination des critères de performance est propre à chaque tâche effectuée par l'opérateur. Un des avantages de ces mesures réside dans le fait qu'elles sont quantitatives. Elles permettent d'estimer la part des ressources cognitives sollicitées par l'opérateur lors de la tâche. En outre, les mesures de performance ne perturbent pas la tâche. En effet dans la plupart des cas, il est possible de mesurer la performance sans avoir besoin d'interrompre l'opérateur dans la réalisation de la tâche.

En revanche, les mesures de performance ne sont pas toujours fiables. Dans certains cas, les opérateurs sont capables de s'adapter à leur charge de travail, notamment grâce à leur entraînement, leurs expériences et leurs stratégies (O'Donnell & Eggemeier, 1986). Et il est alors possible que la performance ne varie que très peu, lorsque la charge mentale de travail change. La limite de l'évaluation de la charge mentale par le biais de la performance a notamment été pointée par Cegarra et Chevalier (2008).

De plus, il est nécessaire de faire la distinction entre faibles performances liées à des ressources disponibles limitées ; et faibles performances liées à la qualité des données actuellement disponibles résultant des caractéristiques de la tâche, de l'expertise de l'opérateur, etc. (Norman & Bobrow, 1975, 1979). Dans le cas des ressources disponibles limitées, la performance serait meilleure si l'opérateur pouvait mobiliser davantage de ressources. Alors que si les limites étaient dues aux caractéristiques de la tâche, une plus grande mobilisation des ressources n'améliorerait pas la performance.

2.3. MESURES PHYSIOLOGIQUES DE L'EFFORT MENTAL

Les mesures physiologiques font référence à la dimension de la charge mentale de travail, appelée effort mental composé lui-même de ressources. Les mesures physiologiques de l'effort mental peuvent être divisées en deux catégories, les mesures neurologiques et les mesures périphériques. Tout d'abord, les mesures neurologiques peuvent être constituées de l'électroencéphalographie (EEG), des potentiels évoqués, de la tomographie par émission de positons (TEP), de l'imagerie par résonance magnétique fonctionnelle (IRMf) et de la spectroscopie proche infrarouge (SPIR). Ces techniques permettent de localiser les changements de l'activité cérébrale en fonction des conditions expérimentales. Ces techniques sont davantage liées à des événements de la tâche qu'à la tâche dans sa globalité. Par exemple, l'amplitude de l'onde P300 témoignerait de la quantité d'effort mental mobilisé. Dans de nombreuses études (Baving, Rockstroh, & Röβner, 2000 ; Causse, Fabre, Giraudet, Gonzalez, & Peysakhovich, 2015 ; Dehais et al., 2019 ; Donchin, Kramer, & Wickens, 1986 ; Falkenstein, Hoormann, & Hohnsbein, 2003 ; Kamijo, Nishihira, & Higashiura, 2007 ; Kida, Nishihira, & Hatta, 2004 ; Mulder, 1986 ; Polich, 1987), une diminution de l'amplitude de la P300 est interprétée comme une mobilisation de l'effort mental. Cependant, il est important de tenir compte du rapport entre le « signal » (produit par la mesure) et le « bruit » (dû aux effets indésirables). Ce rapport signal/bruit a fait l'objet de

nombreuses études sur des mesures physiologiques de la charge mentale de travail (Coffey, Brouwer, & Van Erp, 2012 ; Wilson & O'Donnell, 1988). Même de légères perturbations - comme le clignement des yeux et le serrage des dents apportent un bruit non négligeable, lors de la mesure neurologique. L'effet du bruit indique une limite de ces mesures avec un manque de sélectivité qui inclut des changements non liés uniquement à la charge mentale de travail.

Les mesures périphériques mesurent l'activité nerveuse, telles que l'activité électrodermale (Clarion, 2009 ; Dawson, Schell, & Filion, 2000 ; Gendolla & Krüsken, 2001 ; Gendolla & Richter, 2005), le diamètre pupillaire (Kahneman & Beatty, 1966 ; Peysakhovich, Dehais, & Causse, 2015), l'activité cardiovasculaire (Capa, Audiffren & Ragot, 2008 ; Capa, Cleeremans, Bustin, & Hansenne 2011 ; Richter, Friedrich, & Gendolla, 2008 ; Mazeres, Brinkmann, & Richter, 2019 ; Wright, 1996) et l'activité respiratoire (Mulder, 1992 ; Veltman & Gaillard, 1998). Les mesures périphériques sont généralement utilisées dans la littérature en psychophysiologie comme indices du niveau d'effort mental mobilisé. Ces indices ont la particularité de répondre à des mécanismes sous-jacents communs, notamment le système nerveux végétatif, autonome. Celui-ci est composé de deux branches, le système nerveux sympathique et le système nerveux parasympathique (Berntson, Cacioppo, & Quigley, 1993 ; Sztajzel, 2004). Le système nerveux sympathique a pour fonction de mobiliser les ressources de l'organisme face à toute sollicitation énergétique. Le système nerveux parasympathique vise à économiser la mobilisation des ressources de l'opérateur. De nombreuses études ont été menées afin de déterminer des indicateurs physiologiques majoritairement, ou uniquement sous l'influence du système nerveux sympathique ; isoler de l'activité du système parasympathique. Des études menées par Sherwood et al. (1990) en pharmacologie et par Richter et al. (2008) en psychophysiologie, font apparaître la réactivité cardiovasculaire, et plus précisément la période de pré-éjection (PEP) comme une mesure fiable, valide et précise de l'activité sympathique uniquement sous l'influence du système nerveux sympathique et non soumise au système parasympathique. La PEP est définie comme l'intervalle de temps entre la contraction du ventricule gauche et l'ouverture de la valve aortique (Bernston et al., 2004). La diminution de la

PEP reflète une augmentation de la mobilisation de l'effort que lorsque la fréquence cardiaque et la pression artérielle sont stables ou augmentent (Sherwood et al., 1990).

Les mesures neurologiques de l'effort sont très spécifiques, centrées sur des processus cognitifs précis, liés le plus souvent à un évènement (par exemple la surdité attentionnelle (Giraudet, St-Louis, Scannella, & Causse, 2015). Les mesures périphériques sont plus largement liées à la tâche de manière plus générale.

De manière générale, les mesures physiologiques ont souvent l'avantage d'être prises en continu : un avantage qui n'est généralement pas partagé par les mesures subjectives ni les mesures de performance.

2.4. UNE APPROCHE MULTIPLE

Ces trois groupes de mesures présentent des avantages et des inconvénients, aucun ne se suffisant à lui-même pour évaluer seul la charge mentale de travail. Comme nous l'avons vu dans le premier chapitre, la charge mentale de travail est composée de trois dimensions.

Les exigences de la tâche imposent une certaine charge mentale de travail, qui produit des effets sur l'opérateur. Ces effets peuvent être de trois niveaux : subjectifs, physiologiques et comportementaux. Par exemple, lorsque les exigences de la tâche augmentent, nous pouvons étudier le ressenti (mesure subjective) et dans quelle mesure elle agit sur l'opérateur (mesure physiologique) ; puis, quelle répercussion les exigences génèrent-elles sur la performance (mesure de performance). L'approche multidimensionnelle peut ainsi donner du sens à l'interprétation, en comparant les différentes perceptions. Par exemple, en cas d'effort mental et de performance faibles et de ressenti de la charge mentale de travail élevé, alors nous pouvons interpréter que l'opérateur se désengage face à une surcharge. Ou encore, lorsque l'effort mental mobilisé et le ressenti de la charge mentale de travail sont élevés mais que la performance baisse, alors nous

pouvons interpréter que l'opérateur est engagé dans la tâche mais il arrive au maximum de ces capacités. Il se fatigue.

Cette possibilité de comparaison entre les différentes perceptions explique pourquoi la majorité des approches multiples mises en place dans certaines études antérieures portant sur l'évaluation de la charge mentale, consiste à coupler les mesures physiologiques et subjectives (Hilburn, 2004).

2.5. CONCLUSION INTERMEDIARE

Dans la continuité de notre positionnement théorique avec la définition de Hart et Staveland (1988) et le modèle de la charge mentale de travail de Hancock et Szalma (2006), une approche multiple de la mesure nous paraît l'approche la plus adaptée pour répondre à notre problématique de recherche. En effet, nous avons besoin d'une mesure subjective des exigences de la tâche, de mesures de performance et d'une mesure physiologique.

La mesure subjective sera l'échelle unidimensionnelle d'Eccles and Wigfield (1995) pour plus de sélectivité et un temps de passation réduit, afin d'obtenir un niveau global moyen des exigences de la tâche ressentie. La mesure sera prise à la fin de la tâche expérimentale, afin de ne pas interrompre la tâche.

Les indicateurs de performance seront les plus fréquemment employés et les plus représentatifs dans la littérature, selon la tâche utilisée.

La mesure physiologique sera une mesure périphérique de l'activité cardiovasculaire : la période de pré-éjection (PEP). En accord avec notre positionnement théorique, la PEP avec la fréquence cardiaque et la pression artérielle sont des mesures générales de l'effort mental de la tâche dans sa globalité. D'autre part, les mesures périphériques comme les mesures cardiovasculaires sont des mesures acceptées et utilisées dans le contrôle du trafic aérien (Averty, Collet, Dittmar, Athènes, & Vernet-Maury, 2004 ; Collet, Averty, & Dittmar, 2009).

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La partie expérimentale de ce manuscrit vise à répondre à la problématique de recherche, énoncée comme suit :

Quels sont les effets de la charge mentale de travail sur l'efficacité, notamment l'adaptabilité de l'opérateur ? Pour y répondre, nous nous baserons sur les choix effectués relatifs au cadre théorique et à l'approche méthodologique multiple de l'évaluation de la charge mentale de travail.

Dans le premier article, nous retrouverons le modèle multidimensionnel et dynamique de la charge mentale de travail, de Hancock et Szalma (2006). L'objectif de cet article est de tester l'effet curvilinéaire de la charge mentale de travail sur l'adaptabilité comportementale et physiologique du modèle de Hancock et Szalma (2006), qui n'a jamais été validé expérimentalement dans sa globalité. Pour tester ce modèle à travers une tâche de pointage (Hancock & Caird, 1993 ; Hoffmann, 2011 ; Johnson & Hart, 1987), nous utiliserons la mesure de la période de pré-éjection (PEP) pour mesurer l'effort mental (adaptabilité physiologique), le temps de mouvement et le taux d'erreur pour mesurer la performance (adaptabilité comportementale) ainsi que la difficulté ressentie par l'opérateur, avec l'échelle d'Eccles et Wigfield (1995) pour mesurer les exigences de la tâche ressenties. Nous émettons l'hypothèse d'un effet curvilinéaire des exigences de la tâche sur le temps de mouvement et la PEP.

Dans la continuité de ce travail de recherche, nous allons nous interroger sur les facteurs modulant cet effet curvilinéaire de la charge mentale de travail sur l'adaptabilité comportementale (performance) et physiologique (effort mental). En accord avec le modèle d'Hancock et Szalma (2006) la pression temporelle devrait être un facteur important d'adaptabilité comportementale et physiologique. En effet, comme nous l'avons vu dans la partie théorique, d'autres auteurs comme Brehm et Self (1989) en psychologie expérimentale, trouvent un effet linéaire entre difficulté et effort mental avec une absence d'adaptabilité. Pour cela dans le second article, nous testerons l'importance de l'aspect dynamique du modèle et notamment la pression temporelle, comme

modulateur de cet effet. La pression temporelle aurait alors comme effet de favoriser l'adaptabilité comportementale et physiologique, par le biais de stratégies (Maule & Hockey, 1993).

Ainsi nous aurons testé l'effet curvilinéaire de la charge mentale de travail sur l'adaptabilité comportementale et physiologique du modèle et la modulation de cet effet curvilinéaire avec une forte validité expérimentale en laboratoire.

Dans notre troisième article, avec une plus grande validité écologique à travers un micromonde (Imbert, Hodgetts, Parise, Vachon, & Tremblay, 2014), nous testerons la capacité des tâches de contrôle du trafic aérien (ATC) à faire émerger un tel compromis cognitif (efficacité) se traduisant par une adaptabilité de l'opérateur.

PARTIE EXPÉRIMENTALE

ARTICLE 1

Running head: Mental Workload and Pre-Ejection Period

Topic choice: Cognition

A CURVILINEAR EFFECT OF MENTAL WORKLOAD ON MENTAL EFFORT AND BEHAVIORAL ADAPTABILITY: AN APPROACH WITH THE PRE-EJECTION PERIOD

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Précis/Short abstract: The present study provides the first evidence of physiological and behavioral adaptability as a function of mental workload in agreement with the model of Hancock et al. (2006). It would be interesting to validate cardiac PEP reactivity in other mental workload models in human factors and ergonomics.

Research article

A curvilinear effect of mental workload on mental effort and behavioral adaptability: An approach with the pre-ejection period

Objective: We tested Hancock and Szalma's mental workload model, which has never been experimentally validated at a global level with the measure of the pre-ejection period (PEP), an index of beta-adrenergic sympathetic impact.

Background: Operators adapt to mental workload. When mental workload level increases, behavioral and physiological adaptability intensifies to reduce the decline in performance. However, if the mental workload exceeds an intermediate level, behavioral and physiological adaptability will decrease to protect individuals from excessive perturbations. This decrease is associated with a change in behavioral strategies and disengagement.

Method: The experimental task was a modified Fitts' task used in Hancock and Caird (1993). Five levels of task difficulty were computed. Behavioral and physiological adaptability was indexed by the performance with speed-accuracy trade-off and PEP reactivity.

Results: A curvilinear effect of task difficulty on PEP reactivity was significant, with high reactivity at the intermediate level but low reactivity at other levels. We observed a linear effect of task difficulty on error rate and a curvilinear effect on movement time. A decline in performance was noted up to the intermediate level, with a speed-accuracy trade-off above this level showing a faster movement time.

Conclusion: We observed for the first time behavioral and physiological adaptability as a function of mental workload.

Application: The results have important implications for the modeling of mental workload, particularly in the context of the performance-sensitive domain (car driving and air traffic control). They can help guide the design of human-computer interaction to maximize adaptive behavior, i.e., the 'comfort zone.'

Keywords: Workload, Effort, Performance, Cardiovascular reactivity

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INTRODUCTION

Flying an aircraft varies in difficulty depending on situations. The *task demand* can differ substantially when considering time pressure, task complexity, or the performance levels imposed on the operator (Gopher & Donchin, 1986).

Indeed, an operator has to consider the task demand along with his/her characteristics, such as previous experience with the task (i.e., training). Therefore, when evaluating *mental workload* in performing a task, one has to consider the interaction between characteristics of the task, the operator, and the environment (Hart & Staveland, 1988; Wickens, 2008).

While coping with task demand, operators mobilize cognitive resources, which are drawn from a finite pool of resources. In an ‘energetic’ paradigm, one should consider that operators mobilize their resources dynamically and voluntarily (Hockey, 1997; Kahneman, 1973). In our study, we focused on the relationship between mental workload, mental effort, and performance. We used a state-of-the-art cardiovascular measurement of mental effort, the Pre-Ejection Period (PEP), to test our effort-related hypothesis.

The Relationship between Mental Workload, Mental Effort, and Performance

The effect of mental workload on mental effort and performance is of practical significance, and numerous studies in ergonomics have focused on these relationships. Concerning the effect of mental workload on performance, the insufficient stimulation is known to lead to underload, boredom, and decreased performance (Brookhuis, De Waard, & Fairclough, 2003; Hancock, 2013). Conversely, overload is also known to decrease task performance (Cegarra & Chevalier, 2008).

At the same time, operators are not passive to mental workload increase and as such, they must strategically manage their workload (Moray, Dessouky, Kijowski, & Adapathya, 1991). Strategic management is reflected by changes in strategies and/or performance criteria (Parasuraman & Hancock, 2001). Operators might also differ in their task engagement. Different

authors have suggested that an increase in task demand (mental workload) leads to a superior mobilization of mental effort (Young, Brookhuis, Wickens, & Hancock, 2015). When the task demand exceeds the upper limit of resources, one might observe a strong decrease in effort and performance (Cegarra & Hoc, 2006; Wickens, 2001). These relationships between mental workload, performance, and mental effort are well illustrated in the mental workload model of Hancock (Hancock & Caird, 1993; Hancock & Chignell, 1988; Hancock & Szalma, 2006, 2008; Hancock & Warm, 1989).

A Curvilinear Relationship of Mental Workload with Behavioral and Physiological Adaptability

Hancock and colleagues considered a curvilinear relationship of mental workload with behavioral and physiological adaptability. In this model (Figure 1), behavioral and physiological adaptability varies as a function of stress level. Hancock and Szalma (2006) explicitly recognized that for operators, the primary source of stress is task demand, an important aspect of mental workload. In many stressful situations, operators adapt to their environments. In agreement with Hancock and Szalma (2006), the effort is the cost of resolution and represents the force that acts to oppose the mental workload driven by increasing task demand. The effort is defined here as an adaptive strategy of the operator. Adaptive or compensatory processes depend on the response strategies of a number of body structures that regulate the effects of task demand. Adaptation occurs at a behavioral and physiological level. Psychological adaptability is closely tied to an operator's attentional resource capacity and refers to the behavioral responses, whereas physiological adaptability is related to traditional representations of homeostatic adjustment (Hancock & Warm, 1989). A curvilinear effect of task demand on behavioral and physiological adaptability (Figure 1) illustrates this adaptation.

The level of task demand can vary on a continuum from extremely low to extremely high (i.e., hypostress for very low task demand and hyperstress for very high task demand), and it refers to situations of underload and overload. At a low level of task demand, behavioral and physiological

Workload and Pre-Ejection Period

adaptability is low. However, behavioral and physiological adaptability is predicted to increase proportionally with the level of task demand up to the intermediate level of task demand. Thus, from very low task demand level up to intermediate task demand level, an increase in behavioral and physiological adaptability represents a compensatory mechanism to protect performance or slow down the decline in performance. However, at the intermediate level of task demand, behavioral and physiological adaptability is stable, and operators are in a comfort zone of maximum adaptability. If task demand progresses toward overload (very high task demand), then the level of behavioral and physiological adaptability decreases. According to the Hancock and Szalma's model (2006), when task demand increases and approaches overload, behavioral adaptive strategies can protect the operator from large or excessive perturbations and obviate the need to engage in a costly activity.

This model has been partially validated, although never with both behavioral and physiological measures (Hancock & Szalma, 2006), possibly because a physiological index of mental effort has not been well defined yet.

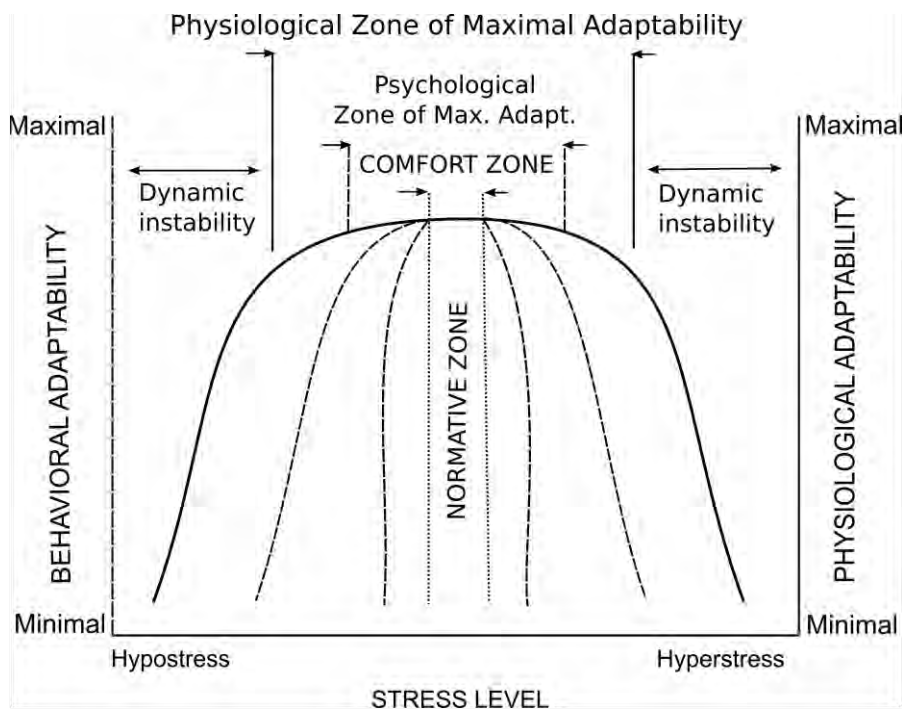


Figure 1. Curvilinear model of the effect of stress level on behavioral and physiological adaptability. The primary source of stress is task demand. Adapted from “Stress and Neuroergonomics” by P.A. Hancock, and J. L. Szalma, 2006, p. 158.

Physiological Reactivity Related to Mental Effort

Physiological measures are frequently used to classify the level of mental effort (Borghetti, Giametta, & Rusnock, 2017; Marinescu et al., 2018). Different physiological measures, such as skin conductance, temperature, heart rate, or pupil dilatation, are frequently used to establish the level of sympathetic nervous system activity (Capa, Audiffren, & Ragot, 2008). Wright (1996) integrated Motivational Intensity Theory (MIT Brehm & Self, 1989) with the active coping approach (Obrist, 1981), showing that beta-adrenergic sympathetic nervous system activity on the heart is an indicator of effort. Following this approach, recent studies have highlighted the time interval between ventricular excitation and the opening of the heart’s left ventricular valve, or PEP (Berntson, Lozano, Chen, & Cacioppo, 2004), as a more reliable and valid index of mental effort mobilization. PEP is an index of beta-adrenergic sympathetic impact (Benschop et al., 1994). It responds to variations in task difficulty (Richter, Friedrich, & Gendolla, 2008) in a large variety of sensory-cognitive tasks (Richter et al., 2016). Furthermore, PEP is a direct indicator of changes in the myocardial contractility force (Sherwood, Dolan, & Light, 1990). Increased myocardial sympathetic activity increases contraction force and decreases PEP. Due to the systematic effect of cardiac contractility on cardiac output (the volume of blood pumped by the ventricles per minute), several studies have also used systolic blood pressure (SBP) to monitor effort (see Richter, Gendolla, & Wright, 2016; Wright & Kirby, 2001 for reviews). However, SBP is influenced by peripheral vascular resistance and is less sensitive to mental effort investment (Levick, 2003). Still, other studies have relied on Heart Rate (HR) as an indicator of effort (e.g., Eubanks, Wright, & Williams, 2002), which is influenced by both sympathetic and parasympathetic activity. Increased HR may be due to increased sympathetic activity, but it can also be the result of the decreased parasympathetic activity. Moreover, at low-intensity levels, increases in cardiac activity are due

mainly to parasympathetic withdrawal (Victor, Seals, Mark, & Kempf, 1987). Increased HR is influenced by increased sympathetic activity only at high-intensity levels. Among these indices, PEP is the most reliable measure of effort mobilization because it can mirror beta-adrenergic sympathetic activity directly (Kelsey, 2012). Nevertheless, PEP should always be assessed together with HR and blood pressure to monitor possible preload (ventricular filling) or afterload (arterial pressure) effects on PEP (Sherwood et al., 1990). If decreases in PEP are not accompanied by simultaneous decreases in HR or blood pressure, we can attribute them to beta-adrenergic sympathetic activity.

Since the physiological adaptability described in the mental workload model of Hancock and Szalma (2006) refers to general processes of resource mobilization and not to specific processes of resource mobilization generally measured with electroencephalography or functional magnetic resonance imaging, the PEP is a good candidate to empirically test this model.

Overview of the Experiment and Hypotheses

Our main hypothesis was examined in a modified Fitts' task with shrinking targets. Five levels of task difficulty were found to increase linearly (very easy, easy, intermediate, very difficult, impossible). In agreement with Hancock and Szalma's model, our predictions were as follows. When task demand increases from very low up to intermediate level, then a stronger behavioral and physiological adaptability should occur to reduce the decline in performance. We expected to observe this decline (i.e., an increase of error rate and movement time [MT]) as well as a stronger PEP reactivity related to the mental effort. In agreement with Hockey (1997) and Kahneman (1973), when task demand increases, effort mobilization reduces the decline in performance and helps individual stay-on-task.

However, if task demand exceeds the intermediate level, then a decrease in behavioral and physiological adaptability should occur to protect individuals from large or excessive perturbations and prevent them from engaging in a costly activity. This decrease in behavioral physiological adaptability would induce a higher error rate and lower PEP reactivity related to the mental effort

(Figure 1). Behavioral adaptability should be on the MT (Hoffmann, 2011). To optimize the emergence of behavioral adaptability, the target in the present study will vanish when it reaches one pixel. In fact, time pressure placed on the participants would be high and participants would modify the behavior by decreasing the MT. If the target size continues to decrease (Hancock & Caird, 1993; Johnson & Hart, 1987) but never vanishes, then the movement could be made in a more relaxed manner, the MT would increase with task difficulty (Hoffmann et al., 2013). Hoffmann (2011) and Hoffmann, Chan, and Dizmen (2013) observed that when task difficulty increased, the participants moved faster to capture the target prior to it disappearing.

To sum up, we postulated a curvilinear effect of task demand on PEP reactivity, with high PEP reactivity at the intermediate level of task demand and low PEP reactivity at other levels. Concerning the behavioral aspect, we proposed a linear effect of task demand on the error rate. We hypothesized that MT would increase up to the intermediate level and then decrease. In fact, we expected to observe a curvilinear effect of task demand on MT and a speed-accuracy trade-off when task demand exceeds the intermediate level.

METHOD

Participants and Design

One hundred and ten postgraduate students at the National University Institute Champollion volunteered to participate. All participants were right-handed and between 18 to 30 years old. All participants had a normal or corrected-to-normal vision and no history of mental, cognitive, cardiac or neurological disorder, substance abuse, or taking psychoactive medications. They were randomly assigned to one of the five difficulty conditions. The distribution of women and men was balanced between experimental conditions, with seventeen women and five men per condition.

Procedure

First, the participants read and signed the informed consent agreement and subsequently answered a few biographical questions (Matthews et al., 1990). Second, the electrocardiogram (ECG) and thoracic impedance cardiogram (ICG) electrodes were installed. The signal was visually verified and validated on the AcqKnowledge software. Third, the participants completed the rest period. A video of a chimney fire was presented on the computer screen for 8 minutes. After that period, the participants received the task instructions. Fourth, they performed 75 trials of training to the experimental task. Fifth, they performed the experimental task at one of the five difficulty levels (according to the random assignment). Finally, they completed the perceived difficulty scale.

A Modified Fitts' Task with Shrinking Targets

Five levels of difficulty. The experimental task was based on the pointing task of Johnson and Hart (1987), which is a modified Fitts' task (Hancock & Caird, 1993; Hoffmann, 2011). First, we computed different levels of task difficulty in accordance with the Fitts' law (Fitts, 1954). The Fitts' Index of Difficulty (ID) is a function of the amplitude (A) and the size of the target (W). It is expressed in pixels with $ID = \log_2 \left(\frac{2A}{W} \right)$. The formula indicates that a fast and accurate movement increases in difficulty with decreasing size of a target and increasing amplitudes. In the present study, we selected five IDs (2, 3, 4, 5, and 6) corresponding to five difficulty levels (very easy, easy, intermediate, very difficult, impossible) with a linear increment.

Consistent with Hancock and Caird (1993), we manipulated the perceived effective time for action with a target shrink time (T_s). More precisely, the shrink time reflected the time after which the target is half of its current size. Such time was determined by the Fitts' law calculation developed by Hoffmann (2011). More precisely, the shrink time corresponded to the initial target's size (w_0) divided by the speed of targets reduction (V_{sc}): $T_s = \frac{w_0}{V_{sc}}$. The target shrinks until it reaches one pixel.

To ascertain that the five selected IDs produce a linear performance decrement with the shrinking targets, we conducted a pretest with ten participants. In this pretest, we manipulated, in agreement with Hoffmann (2011), different T_s (100, 200, 400, 800, and 1600 msec) based on our five difficulty levels, and we analyzed error rate as an index of difficulty. Our analyses revealed that the error rate increased linearly according to the levels of difficulty, i.e., IDs that represent task demand. The most notable increase was observed at 200 msec. This value was selected for the experiment.

Experimental task. Each trial had two amplitudes of movement, 50 and 67.7 mm, which were counterbalanced across levels. The amplitudes were calculated with Fitts' law and in accordance with our IDs. Two amplitudes were used to minimize the learning effect of the participants. Moreover, as the two amplitudes of the movement were counterbalanced across task demand conditions, any difference in PEP reactivity would indicate a change in mental effort mobilization rather than a change in physical effort.

The initial target sizes for selected IDs were 96, 48, 24, 12, and 6 pixels with an amplitude of 50 mm and 128, 64, 32, 16, 8 pixels with an amplitude of 67.7 mm, respectively. The experiment consisted of 150 trials, and each trial was divided into four successive screens (Figure 2). During the preparation phase, only the start position was presented. In the execution phase, the pointer and the targets appeared. The participants were previously instructed to move and click on the targets with the mouse as quickly and precisely as possible. Displacements were limited to the horizontal plane. When a target was clicked, it disappeared while the start position remained on the screen. Finally, the 'return' phase was an empty screen. Each trial lasted 5,700 milliseconds.

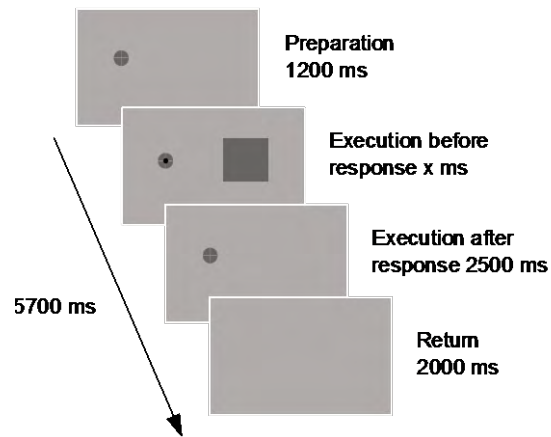


Figure 2. Successive screens displayed for one trial of the pointing task with shrinking targets.

Cardiovascular Measures and Analyses

Cardiovascular measures (PEP, HR, SBP, DBP) were collected during the rest period (8 minutes) and during the experimental task (15 minutes). PEP (in milliseconds [ms]) and HR (in beats per minute [bpm]) were measured continuously using a Biopac MP160 system that sampled ECG and ICG signals at 2000 Hz. For the ECG, three electrodes were placed on the right and left shoulder and down to the end of the coasts. For the ICG, electrodes were placed on the right and left sides of the base of participants' neck and on the left and right middle axillary line at the height of the xiphoid. A digital automatic blood pressure monitor (OMRON-MIT Elite) was used to measure arterial pressure (SBP and DBP) in millimeters of mercury (mmHg). The blood pressure cuff was placed over the brachial artery above the elbow of the participants' non-dominant arm and was automatically inflated at 1-min intervals. Neither participants nor experimenter were aware of the values during the experiment.

PEP and HR signals were analyzed with the AcqKnowledge 5.0 software. PEP was determined as the time interval (in ms) between R-onset and B-point (Berntson et al., 2004). The R-onset and the B-point were automatically scored for each artifact-free ensemble average. The B-point location was estimated based on locations of R and C points according to polynomial

equation proposed by Lozano et al. (2007), and it was visually inspected and corrected, if necessary (Sherwood et al., 1990).

Rest period. The rest period lasted 8 minutes. During this period, PEP and HR measures were continuously recorded and averaged for each minute, resulting in 8 means. Eight arterial pressure measures (SBP and DBP) were taken at 1 min intervals, resulting in 8 measures. Baseline scores were averaged over the three successive lowest means (i.e., PEP and HR) or measures (i.e., SBP and DBP). Cronbach's α values were .99 for PEP baseline, .99 for HR baseline, .98 for SBP baseline, and .93 for DBP baseline scores.

Experimental task. The experimental task lasted 15 minutes. PEP and HR scores were continuously recorded and averaged for each minute, resulting in 15 means. Arterial pressure (SBP and DBP) was measured after every 50-trial block during the experimental task (50th, 100th, and 150th trial), resulting in 3 measures. Cardiovascular measures during the experiment had high internal consistencies. Cronbach's α values were .99 for PEP, .99 for HR, .94 for SBP, and .66 for DBP. The arithmetic mean of the three arterial pressure measures during task performance served as an experimental task score. PEP and HR experimental task scores were based on the measures obtained during the 15 minutes of the experimental task.

Cardiovascular reactivity. Each cardiovascular reactivity score was calculated by subtracting the baseline scores of the rest period from the experimental task scores of the experimental task (Llabre, Spitzer, Saab, Ironson, & Schneiderman, 1991).

Behavioral Measures

The performance was measured by error rate (in %) and MT (in milliseconds [ms]). MT is the time it took the participants to click on the target once the movement has been initiated. Only the MTs of the correct responses were examined. Since manipulating the Fitts' law had a large and systematic effect on MT and a relatively small effect on reaction time (Fitts & Peterson, 1964), we focused on MT.

Subjective Measures

The French version of the Eccles and Wigfield's (1995) scale was used to evaluate perceived difficulty. This scale has good psychometric properties and is sensitive to differences in difficulty levels (Capa, Audiffren, & Ragot, 2008). It comprises 4 items measured on a scale from 1 (very easy) to 5 (impossible) (What is the difficulty level of this task for you?, Compared to difficulties experienced by other participants in this study, this task is..., Compared to the difficulty of most other tasks in daily life, this task is..., How hard is this task for you?).

Statistical Analysis

Based on our theoretical assumptions, the curvilinear effect of task demand on PEP reactivity was analyzed with a curvilinear polynomial contrast. Quadratic contrast weights were 2, -1, -2, -1, 2 for the difficulty levels from very easy to impossible. Concerning behavior analyses, we tested the linear effect of difficulty levels on error rate with a linear polynomial contrast. Linear contrast weights were -2, -1, 0, 1, 2 for the difficulty levels from very easy to impossible. Subsequently, we tested the curvilinear effect of task difficulty on MT with curvilinear polynomial contrasts. Quadratic contrast weights were 1 for very easy, -1 for easy, -1 for intermediate, and 1 for very difficult. As the error rate in the impossible condition would be close to 100 %, very few data would be available for the impossible level of difficulty of MT. Finally, we analyzed subjective difficulty scores with a one-way ANOVA (5 levels of task demand).

RESULTS

Cardiovascular Results

Cardiovascular baseline. We used a one-way ANOVA (5 levels of difficulty) for any baseline index to examine whether the groups differed in their rest periods. No differences between groups

were found ($p_s > .17$). Means and standard errors of baseline scores by difficulty levels are reported in Table 1.

Cardiovascular reactivity. The quadratic contrast of difficulty levels on PEP reactivity scores was significant ($F(1,105) = 7.69, p < .01, \eta_p^2 = .07$) and captured all significant variance (residual, $F < 1$). PEP reactivity scores were high for intermediate level ($M = -8.22, SE = 3.57$) and low for other levels of difficulty ($M = -1.56, SE = 1.71$ for very easy; $M = -0.72, SE = 0.86$ for easy; $M = -3.21, SE = 1.71$ for very difficult; $M = 2.36, SE = 0.95$ for impossible) (Figure 3). Decomposing this curvilinear effect using focused comparisons between conditions revealed a significant difference between easy and intermediate ($F(1,42) = 4.26, p < .04, \eta_p^2 = .09$), intermediate and impossible ($F(1,42) = 8.49, p < .001, \eta_p^2 = .17$), and very difficult and impossible ($F(1,42) = 8.10, p < .01, \eta_p^2 = .16$) levels. No significant difference was found between other levels ($p_s > .09$).

Table 1. Means (standard errors) of cardiovascular baseline scores

	Difficulty levels				
	Very easy	Easy	Intermediate	Very difficult	Impossible
PEP	110.80 (2.77)	107.76 (1.57)	110.05 (2.26)	111.29 (2.11)	108.45 (1.93)
HR	79.95 (2.38)	80.82 (2.52)	82.09 (2.62)	75.96 (2.61)	81.68 (2.26)
SBP	110.86 (1.93)	113.38 (1.57)	112.98 (2.04)	111.62 (2.41)	115.05 (1.68)
DBP	74.09 (1.79)	73.80 (1.77)	72.48 (1.67)	74.36 (2.02)	73.26 (1.82)

Note. N = 22 for all cells. PEP: Pre-Ejection Period, HR: Heart rate, SBP: Systolic Blood Pressure, DBP: Diastolic Blood Pressure. The pre-ejection period was measured in milliseconds (ms) and heart rate in beats per minute (bpm). Systolic blood pressure and diastolic blood pressure were measured in millimeters of mercury (mmHg).

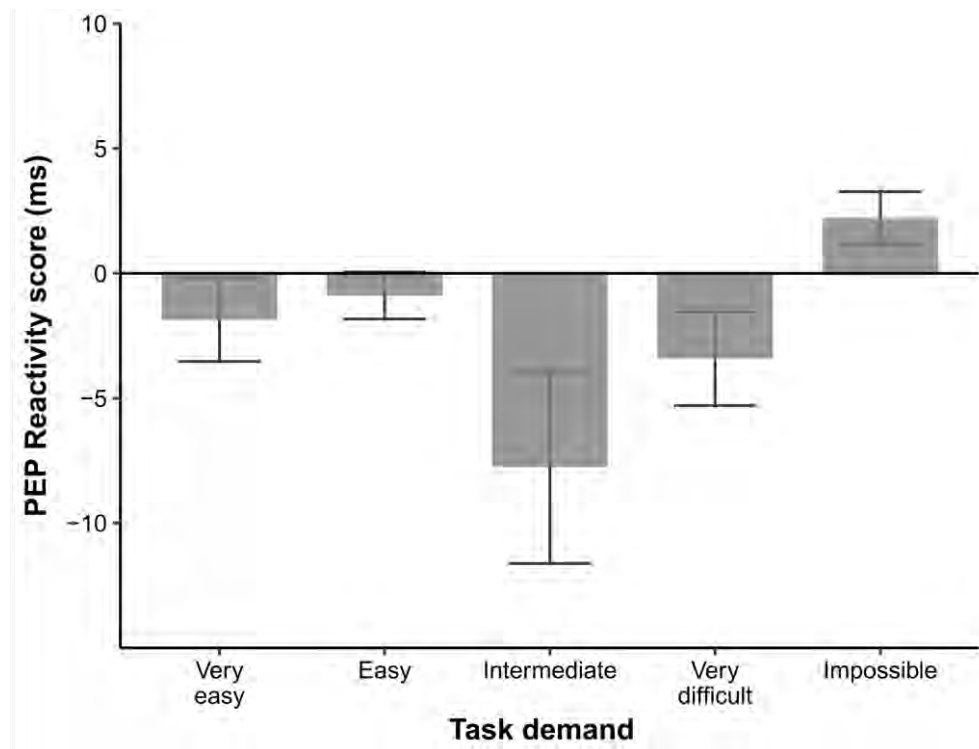


Figure 3. Mean pre-ejection reactivity scores (milliseconds) by task demand. Error bars represent standard error.

We examined whether PEP reactivity scores differed as a function of time-on-task with complementary ANOVAs. No difference was found ($p_s > .19$).

Behavioral Results

Error rate. The linear contrast of difficulty levels on error rate was significant ($F(1,105) = 936.76, p < .001, \eta_p^2 = .90$) (residual, $F < 1$). Means and standard errors were $M = 10.18$ (2.35) for very easy, $M = 22.69$ (2.90) for easy, $M = 52.03$ (3.29) for intermediate, $M = 80.94$ (2.31) for very difficult, and $M = 100$ (0) for impossible (Figure 4). Decomposing this effect by means of one-way ANOVAs showed significant differences across all conditions ($p_s < .01$ and $\eta_p^2 > .21$).

MT. The quadratic contrast of difficulty levels on MT was significant ($F(1,84) = 9.58, p < .01, \eta_p^2 = .09$) (residual, $F < 1$). Means and standard errors were $M = 1238.25$ (52.32) for very easy, $M = 1304.37$ (42.36) for easy, $M = 1322.44$ (48.59) for intermediate, and $M = 1112.30$ (32.72) for very difficult (Figure 4).

Complementary, focused comparisons between conditions revealed a significant difference of very difficult level with very easy ($F(1,42) = 4.16, p < .05, \eta_p^2 = .09$), easy ($F(1,42) = 12.87, p < .001, \eta_p^2 = .23$), and intermediate ($F(1,42) = 12.87, p < .001, \eta_p^2 = .23$) levels. No other difference was significant ($ps > .33$).

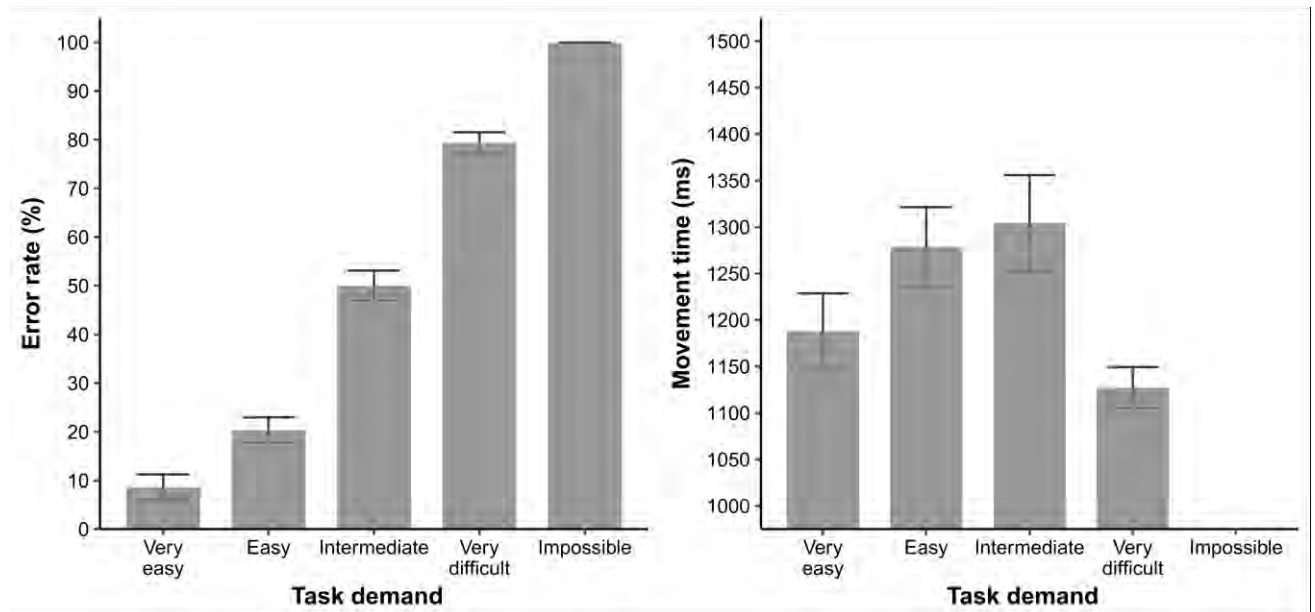


Figure 4. Means of error rate (percentage) and MT (milliseconds) by task demand. Error bars represent standard error.

Subjective Results

Perceived difficulty. The one-way ANOVA revealed a significant effect of task difficulty on the perceived difficulty, $F(4,105) = 12.08, p < .001, \eta_p^2 = .10$. Perceived difficulty increased across different levels. Means and standard errors were $M = 2.04 (0.10)$ for very easy, $M = 2.25 (0.14)$ for easy, $M = 2.41 (0.12)$ for intermediate, $M = 2.49 (0.13)$ for very difficult, and $M = 3.35 (0.17)$ for impossible.

DISCUSSION

We investigated the curvilinear relationship of mental workload on behavioral and physiological adaptability, as postulated by Hancock and Szalma (2006) (Figure 1). To address this

research topic, we used cardiac PEP reactivity, a more reliable and valid index of mental effort mobilization (Richter et al., 2008).

Manipulation of Mental Workload

The perceived difficulty scores and error rate increased across the 5 levels of task demand. These results suggest that experimental manipulation of mental workload was successful.

PEP Reactivity and Mental Workload

PEP reactivity supported our predictions about task demand effects derived from Hancock and Szalma's model (2006). The curvilinear effect of mental workload on PEP reactivity was significant (Figure 3). PEP reactivity scores were high at the intermediate level and low at other levels of task demand. In contrast to PEP reactivity, task demand effects on HR, SBP, and DBP were not significant. The lack of effects of these cardiovascular measures is not surprising, as PEP is an index of beta-adrenergic influence on the heart. Moreover, it is important to note that decreases in PEP reflect increases in beta-adrenergic activity only when HR and blood pressure are stable or increase (Sherwood et al., 1990). As HR and blood pressure were stable in the present study, we concluded that beta-adrenergic effect caused the present PEP responses, reflecting mental effort mobilization (Wright, 1996).

Behavior, PEP Reactivity, and Mental Workload

As expected, we observed a linear effect of task difficulty on error rate and a curvilinear effect on MT (Figure 4). Moreover, PEP reactivity scores increased up to the intermediate level (Figure 3). Taken together, these results suggest that participants mobilized more mental effort to compensate for the decline in performance and to cope with the increase in task demand. However, when task demand increased above the intermediate level (i.e., very difficult level), error rate continued to increase but MT decreased. Moreover, the PEP reactivity scores decreased for the

very difficult level, suggesting that the participants invested less mental effort. In fact, the speed-accuracy trade-off observed for very difficult level as a function of an increase of MT could not be interpreted as a higher mobilization of mental effort but as a disengagement. In agreement with the model of Hancock and Szalma (2006), when task demand increased and approached overload, the participants reduced mental effort investment by using a behavioral strategy. Since the participants believed that they had a low probability to attain the target, they probably decided to change the strategy and move faster to the targets (Hoffmann, 2011; Hoffmann et al., 2013).

These results are consistent with previous studies on the role of behavioral adaptation to keep mental effort within acceptable limits. For instance, Loft et al. (2007) reviewed all factors predicting mental workload of air traffic controllers to propose a model emphasizing the controllers' ability to maintain their mental workload under acceptable levels by means of different behavioral adaptation. Interestingly, they identified different means of behavioral adaptations in real tasks, such as the reordering of task priorities or the management of resources through explicit control of the airspace.

The Relationship between Subjective Measures of Task Demand and Mental Effort

A common idea postulated by the MIT (Brehm & Self, 1989) is that mental effort mobilization is a linear function of subjective task demand, as long as success is possible and justified. This relation was confirmed in several studies using cardiovascular measures and PEP reactivity (Richter et al., 2016). However, in the present study, perceived difficulty increased across the level of task demand, and we observed an increase of PEP reactivity up to the intermediate level and a decrease after the intermediate level. Contrary to the expectations and results of studies using the MIT theory, PEP reactivity related to effort did not increase up to the maximally possible and justified level and thus did not collapse afterward. Instead, the present study revealed a curvilinear relationship with a higher level of effort mobilization at an intermediate level of task

difficulty, whereas the MIT predicted a shark-fin shaped function with a higher level of effort mobilization at a very difficult level.

This difference could stem from the nature of the mental workload used in the present experimental task. Based on Hoffmann (2011) and Hoffmann et al. (2013), we used shrinking targets until reaching one pixel. In fact, the time pressure was high in the very difficult condition, and the participants had faster MTs to capture the target prior to it disappearing. At this very difficult level, a speed-accuracy trade-off was observed; hence, it was not necessary for the participants to invest more mental effort. Such speed-accuracy trade-off was generally not present in the studies conducted with the MIT. For example, neither speed-accuracy trade-off nor change in behavioral adaptability across different levels of difficulty was found in the study of Richter et al. (2008). Therefore, the participants had probably used the same strategy across different levels of difficulty. They invested greater mental effort to reduce the decline in performance up to the maximally possible and justified level of effort. In professional and performance-critical environments, Hancock and Szalma (2006) found that goal distance and time pressure are two main sources of mental workload for the operators. The operator's adaptability at the behavioral and physiological level is predicted to counteract the effects of goal distance and time pressure. Further studies should test whether time pressure influences adaptability and the relationship between subjective difficulty and mental effort.

The second explanation for this curvilinear relation may be related to differences between difficulty levels in subjective importance. Subjective difficulty and subjective importance are generally moderately correlated (Eccles & Wigfield, 1995). When the participants score higher on subjective difficulty, they score lower on subjective success. Referring to MIT, subjective success determines the level of maximally justified effort. In the present study, one possibility is that participants have invested mental effort as a function of subjective difficulty up to the intermediate level. However, above this level, mobilization of effort may have been determined by the low level of maximally justified effort, resulting in a progressive disengagement and a curvilinear effect.

Further studies should compare the subjective success and difficulty to disentangle these respective contributions.

KEY POINTS

- In ergonomics, Hancock and Szalma (2006) regularly postulated behavioral and physiological adaptability as a function of mental workload. However, these predictions never received a clear experimental validation.
- We tested Hancock and Szalma's (2006) predictions of mental workload model with a cardiovascular measure related to mental effort mobilization. We used the pre-ejection period (PEP), an index of beta-adrenergic sympathetic impact.
- The results provided the first evidence for a curvilinear effect of mental workload on PEP reactivity and behavioral adaptability as a function of mental workload.

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ARTICLE 2

Running head: Time Pressure

TIME PRESSURE MODULATES THE CURVILINEAR EFFECT OF MENTAL WORKLOAD ON BEHAVIORAL AND PHYSIOLOGICAL ADAPTABILITY

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Research article

Abstract

We investigated whether the curvilinear relationship of mental workload on physiological and behavioral adaptability, postulated by Hancock and Szalma (2006) and demonstrated by Mallat et al. (2019), is modulated by time pressure. In agreement with Hancock et al., time pressure should be an important factor in behavioral and physiological adaptability when task approaches overload. However, this has never been experimentally validated. To address this issue, participants performed a modified Fitts' task with time pressure (shrinking targets) or without (fixed targets) at five levels of difficulty. Behavioral and physiological adaptability was indexed by performance and Pre-Ejection Period (PEP) reactivity related to effort mobilization. Under both conditions of time pressure, we observed a curvilinear effect of task difficulty on PEP with high reactivity at intermediate level and low at other levels. When task approached overload (i.e., very difficult level), participants disengaged in both conditions, but PEP reactivity was higher under time pressure than without. Moreover, a curvilinear or a linear effect of task difficulty on movement times was observed with and without time pressure conditions, respectively. As the error rate increased linearly in both conditions, this suggested a speed-accuracy trade-off in the time pressure condition. Compared to no time pressure, participants mobilized more effort in time pressure condition to slow the decline in performance and used a new behavioral strategy (speed-accuracy trade-off). Consistent with Hancock and Szalma (2006), this study offered the first demonstration that time pressure encouraged behavioral and physiological adaptability above an intermediate level of difficulty.

Keywords: Mental workload, time pressure, behavioral and physiological adaptability, effort, cardiovascular reactivity

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1. Introduction

Faced with a growing technological evolution-oriented design and automation, studying the adaptability of the operator mental capacities arouses genuine interest. Therefore, when evaluating the mental workload in the execution of a task, the interaction between the task demand, the operator, and the environment must be considered (Hart and Staveland, 1988; Wickens, 2008). Hancock and Warm (1989) proposed two dimensions—information rate (time pressure) and information structure (difficulty)—along which tasks vary. Combined variations in task and environment impose considerable task demands to which operators adapt via a variety of coping efforts.

1.1. *Curvilinear effect of mental workload on behavioral and physiological adaptability*

In ergonomics and cognitive psychology, the Hancock et al.'s dynamic model of mental workload has been suggested to better integrate the concepts of mental workload, mental effort, and adaptability (Hancock and Warm, 1989; Hancock and Caird, 1993; Hancock and Chignell, 1988; Hancock and Szalma, 2006, 2008; Young et al., 2015). Mental effort is the force that opposes the mental workload driven by increasing task demand (Hancock and Szalma, 2006). Mental effort is an adaptive strategy and a compensatory process which regulates effects of task demand. Adaptation could be at a behavioral and physiological level. Psychological adaptability refers to operator's attentional resource capacity and behavioral responses. In contrast, physiological adaptability is tied to homeostatic adjustment (Hancock and Warm, 1989).

The authors propose a curvilinear relationship of mental workload with behavioral and physiological adaptability (see Fig. 1). In this model, behavioral and physiological adaptability varies as a function of stress level. Task demand is the primary source of stress and can range from extremely low to very high. At a hypostress level, task demand is very low and individuals are in a situation of underload. Inversely at a hyperstress level, task demand is very high and individuals are in a situation of overload.

From the very low to the intermediate task demand level, an increase in behavioral and physiological adaptability allows an individual to maintain his/her performance or minimize the decline in performance. At the same time, the overload zone implies the loss of control of the situation because the task demand is too high. The individual is no longer able to mobilize resources to guarantee a minimum of performance. Between the two extremes, there is an intermediate "comfort zone" where the task demand is such that the individual mobilizes an efficient level of mental effort, and the time required for actions is perceived as sufficient (Hancock and Caird, 1993).

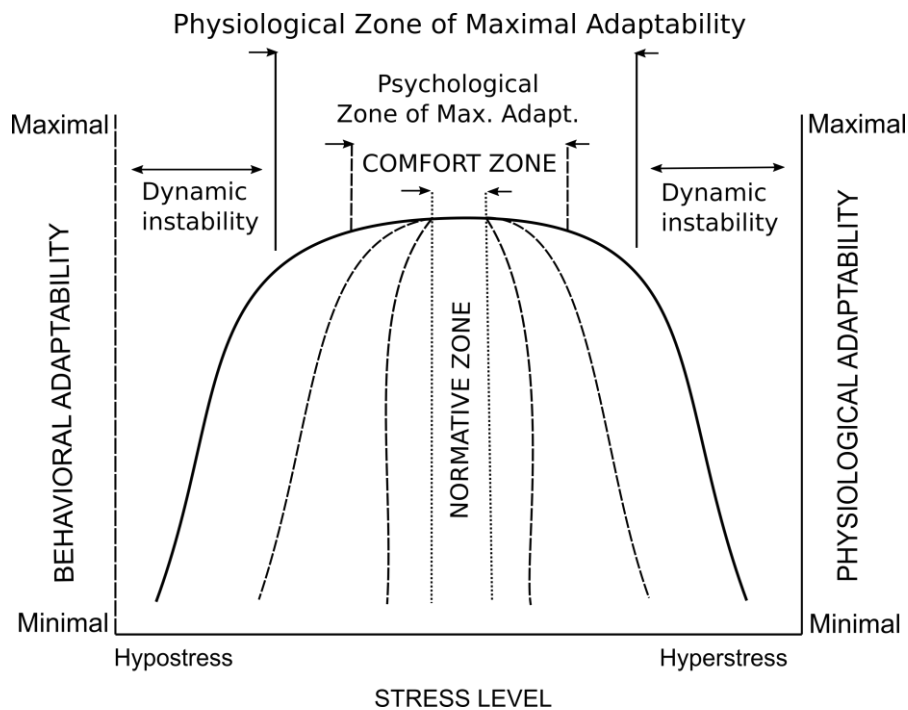


Fig. 1. Curvilinear effect of stress level on behavioral and physiological adaptability. Task demand is the primary source of stress. Adapted from “Stress and Neuroergonomics” by P.A. Hancock, and J. L. Szalma, 2006, p. 158.

The mental workload model of Hancock and Szalma (2006) received partial support but has never been experimentally validated at a global level. Only one recent study by Mallat et al. (2019) validated this curvilinear relationship by using a cardiovascular approach related to effort. In this study, participants performed a modified Fitts’ task based on Hancock and Caird (1993) and

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composed of five levels of task difficulty. The results showed that up to the intermediate level, participants had a stronger cardiac effort activity to reduce the decline in performance (i.e., increase in error rate and MTs). Above this level, a disengagement with lower cardiac effort activity and a speed-accuracy trade-off (i.e., an increase in error rate but a decrease in MTs) occurred. As expected, a curvilinear effect of task difficulty on MT and on cardiac effort activity was observed. This study was the first experimental demonstration of a curvilinear relationship of mental workload on behavioral and physiological adaptability.

1.2. Time pressure an important factor of behavioral and physiological adaptability

Time pressure is omnipresent in work (Lichacz, 2017; Yang and Dattel, 2017; Zhai et al., 2004) and day-to-day situations (Bowden et al., 2017; Rendon-Velez et al., 2016). It involves a conflict between the available time to complete a task and the duration it really takes (Rastegary and Landy, 1993). Time pressure often imposes considerable stress and workload on individuals (Warm et al., 2008). More precisely, Maule and Hockey (1993) identified that under high time pressure, increasing effort or adopting strategies protects individuals from excessive load.

Behavioral adaptability in high time pressure induces speed accuracy trade-off in Fitts' tasks (Plamondon and Alimi, 1997, Rozand et al., 2015), and it was well expressed in the experiments on Fitts' tasks conducted by Hoffmann (2011) and Hoffmann et al. (2013). As in our previous study (Mallat et al., 2019), time pressure was induced with shrinking targets. In this condition, MT decreased with an increase in task difficulty. Participants had faster MTs to capture the target prior to it disappearing (Hoffmann, 2011). However, if targets never disappeared (i.e., without time pressure condition), MT increased with increased task difficulty, as traditionally observed in Fitts' task (Plamondon and Alimi, 1997). MT could be made in a more relaxed manner (Hoffmann et al., 2013).

The comparison of the two studies by Hoffmann suggests that the behavioral adaptive strategy (i.e., faster MTs in a time pressure condition and longer MTs in a without time pressure condition) is modulated by time pressure. This is consistent with the prediction of Hancock that adaptability

is modulated by time pressure. However, this finding was never validated at both a behavioral and a physiological level in a single study. The previous demonstration of Mallat et al. (2019) was achieved with a modified Fitts' task using shrinking targets, which imposed a constant time pressure on the participants. Time pressure should have been an important factor of this behavioral and physiological adaptability (Hancock and Szalma, 2006; Hoffmann, 2011). However, time pressure was not manipulated. The purpose of the present study was to clarify the effect of time pressure on behavioral and physiological adaptability by using a similar experimental task to Mallat et al.'s study (2019) and by manipulating time pressure.

1.3. Physiological indicators of mental effort

Mental effort mobilization is frequently quantified by the reactivity of the physiological system (Bijleveld et al., 2009; Capa et al., 2008a, 2008b, 2011; Fairclough and Ewing, 2017; Fairclough and Houston, 2004; Gendolla et al., 2008; Stuiver et al., 2014). Different measures are frequently used to determine the level of beta-adrenergic sympathetic nervous system activity. Wright (1996) integrated motivational intensity theory (MIT) (Brehm and Self, 1989) with the active coping approach (Obrist, 1981), showing that beta-adrenergic sympathetic nervous system activity on the heart is an indicator of effort. Following this approach, recent research on cardiovascular reactivity highlighted the Pre-Ejection Period (PEP) as an index of mental effort (Framorando and Gendolla, 2019; Freydefont et al., 2016; Richter et al., 2016, 2008). Berntson et al. (2004) defined PEP as the time interval between the beginning of the excitation of the left ventricle and the opening of the aortic valve. PEP is a pure index of the beta-adrenergic sympathetic effect (Benschop et al., 1994) and is a direct indicator of the myocardial contractility force changes (Newlin and Levenson, 1979; Sherwood et al., 1990). PEP decreases with increased myocardial contraction. Measures of cardiovascular activity such as systolic blood pressure (SBP), diastolic blood pressure (DBP), and heart rate (HR), are also indicators of mental effort (e.g., Capa et al., 2008a; Hidalgo-Muñoz et al., 2018). However, SBP and DBP are determined by beta-adrenergic sympathetic nervous system and by peripheral vascular resistance. SBP is less sensitive to mental effort investment than PEP

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(Levick, 2003). DBP is highly influenced by changes in total peripheral resistance and is even less sensitive. HR is determined by both sympathetic and parasympathetic activation and could only reflect effort mobilization when the sympathetic impact is stronger. An increase of HR may be due to increased sympathetic activity and also to decreased parasympathetic activity.

1.4. Overview of the experiment and hypotheses

We tested our predictions in a modified Fitts' task with or without time pressure. For each time pressure condition, we identified five task difficulty levels that increased linearly (very easy, easy, intermediate, very difficult, impossible). According to Hancock and Szalma (2006), when task demand increases from very easy to intermediate, a stronger behavioral and physiological adaptability should occur to reduce the decline in performance (Fig. 1). An increase in error rate and MT, as well as a stronger cardiac PEP reactivity related to the mental effort, were expected. For each condition of time pressure and until the intermediate level of task difficulty, participants should mobilize more effort to reduce the decline in performance and stay-on-task. Participants should use this adaptive strategy until the intermediate level.

As expected by Hancock and Szalma (2006), the difference between behavioral and physiological adaptability as a function of time pressure should appear at the very difficult level when task demand exceeds the intermediate level. At this level, a decrease in behavioral and physiological adaptability should occur to protect individuals from excessive demand (Fig. 1). For both time pressure conditions, this decrease in behavioral and physiological adaptability would induce higher error rate and lower PEP reactivity related to mental effort. In the without time pressure condition, we expected to observe the classical effect of increased MT (Hoffmann et al., 2013; Plamondon and Alimi, 1997). However, time pressure should modulate this new adaptive strategy (Hancock and Szalma, 2006). At the very difficult level, participants should move faster to capture the target prior to it disappearing in the condition of time pressure compared to the without time pressure condition (Hancock and Szalma, 2006; Hoffmann, 2011; Mallat et al., 2019). This

behavioral adaptive strategy should induce greater engagement to try to capture the target in the time pressure compared to the without time pressure condition.

In conclusion, for each condition of time pressure, we postulated a curvilinear effect of task demand on PEP reactivity, with high PEP reactivity at the intermediate level of task demand and low PEP reactivity at other levels. Most importantly, as physiological adaptability depends on time pressure, we should observe a higher PEP reactivity in the very difficult level in the condition of time pressure compared to the without time pressure condition. Concerning the behavioral aspect, we postulated a classical linear effect of task demand on error rate for both conditions of time pressure (Hoffmann, 2011; Hoffmann et al., 2013). For the time pressure condition, we postulated a curvilinear effect of task difficulty on MT. MT would increase up to the intermediate level and then decrease with time pressure. However, in the without time pressure condition, we expected a linear effect of task demand on MT, with MT increasing along with task demand. The difference in behavioral adaptability as a function of time pressure should be observed in a very difficult condition, with faster MT in the condition of time pressure.

2. Method

2.1. Participants

Two hundred and fifty right-handed healthy postgraduate students (190 women, 60 men) enrolled at the National University Institute Champollion volunteered to participate. All participants signed the informed consent before the experiment. They were randomly assigned to one of the 10 groups (i.e., 5 task difficulty groups [very easy, easy, intermediate, very difficult, impossible] \times 2 time pressure groups [with vs. without]). The distribution of women and men was balanced with 19 women and six men in each group, resulting in 25 participants in each group.

There were 125 participants for the time pressure condition and 125 participants for the without time pressure condition. For the time pressure condition, as the experimental demonstration of our hypotheses is very costly in terms of participants and as the experimental task is similar to

Mallat et al.'s, we completed our previous sample. Data of 15 new participants were added (i.e., three new participants by group of task difficulty) to the sample of 110 participants used by Mallat et al. (2019). We added these 15 new participants to confirm the robustness of results (Cohen, 1992, 2013). In the without time pressure condition, 125 participants were recruited for this study to test our hypotheses on time pressure on behavioral and physiological adaptability.

2.2. Procedure

After providing informed consent, participants answered several biographical questions as proposed by Matthews et al. (1990). The cardiovascular electrodes (ECG, ICG) were then attached and AcqKnowledge was used to examine the signal. A digital blood pressure monitor was also attached. Participants were given a rest period during which an 8-minute video of a chimney fire played on the computer screen.

Next, participants received the task instructions and performed 75 trials of training. For the experimental task, participants were randomly assigned to one of the 10 conditions. Finally, they had to complete a perceived difficulty scale.

2.3. Experimental task

The experimental task was based on the modified Fitts' task used by Johnson and Hart (1987) (see also Hancock and Caird, 1993; Hoffmann, 2011; Hoffmann et al., 2013; Mallat et al., 2019). The task comprised 150 trials. Each trial was composed of four successive phases (Fig. 2). In the preparation phase, there was only a start position on the screen. In the execution phase before response, the pointer and the target were displayed simultaneously. The participants received the instructions to move and click on the target with the mouse as quickly and accurately as possible. Once the target was clicked, it disappeared, but the start position remained on the screen. Finally, the return phase led to an empty screen. Each trial lasted 5700 milliseconds. The main difference between task with and without time pressure was our use of shrinking targets (i.e., time pressure condition) or fixed targets (without time pressure condition).

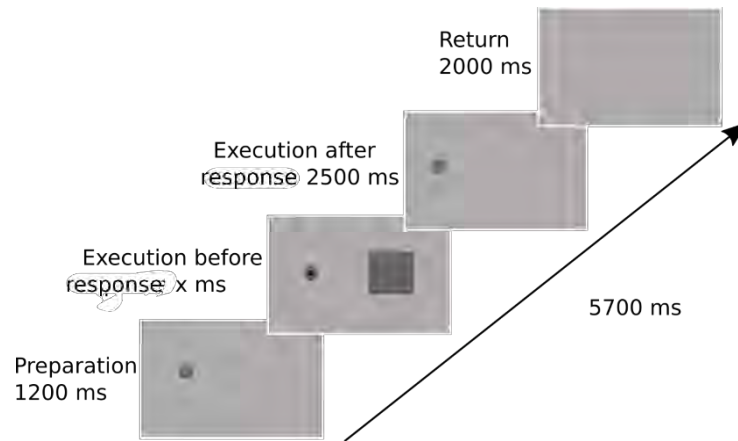


Fig. 2. Sequence of screens used for one trial of the pointing task in both conditions of time pressure.

2.4. Modified Fitts' task with time pressure

In the first step, we calculated different levels of difficulty in accordance with the Fitts' law (Fitts, 1954)¹. We selected five indices of difficulty (IDs, i.e., 2, 3, 4, 5 and 6) corresponding to five task difficulty levels (very easy, easy, intermediate, very difficult, impossible) with a linear increment.

To manipulate time pressure, we used targets shrinking with elapsed time. The shrink time was determined by a calculation based on Fitts' law and developed by Hoffmann (2011). According to Hoffmann, the shrink time is defined as the time required for the target to reduce its size by half.²

We conducted a pre-test with 10 participants to ascertain that the five IDs selected (i.e., 2, 3, 4, 5 and 6) increased linearly. In this pre-test, we manipulated different shrink times (100, 200, 400, 800 and 1600 ms) based on our five difficulty levels. The analyses revealed that error rate, used as ID, increased linearly according to difficulty levels especially with a shrink time of 200 ms. We selected this constant time of shrinking of 200 ms for the experimental task.

¹ The Fitts' index of difficulty (ID) is a function of the amplitude (A) and the size of the target (W) expressed in pixels: $ID = \log_2 \left(\frac{2A}{W} \right)$

² The shrink time (T_S) corresponds to the initial targets size (w_0) divided by the speed of targets reduction (V_{sc} : $T_S = \frac{w_0}{V_{sc}}$).

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Across the different levels of difficulty, two amplitudes of movement (50 and 67.7 millimeters) were counterbalanced. The amplitudes were calculated according to the Fitts' law and our IDs. We used two amplitudes to minimize a learning effect of the participants.

For the amplitude of 50 mm, the initial target sizes as a function of IDs were 96, 48, 24, 12, and 6 pixels. For the amplitude of 67.7 mm, the initial target sizes as a function of IDs were 128, 64, 32, 16, and 8 pixels.

Modified Fitts' task without time pressure

This task was similar to modified Fitts' task with time pressure except no time pressure was imposed and the target was fixed.

In the first step, we ascertained that the difficulty levels in the with and without time pressure conditions were comparable, and we conducted a pretest with 10 participants to determine the five IDs. The analyses revealed that the error rate increased linearly with similar values in both with or without time pressure conditions according to the task difficulty with IDs 4.58, 5.58, 6.58, 7.58 and 8.58 corresponding to five difficulty levels (very easy, easy, intermediate, very difficult, impossible).

Two amplitudes of movement, 52 and 76.2 (millimeters), were counterbalanced across the different levels of difficulty. For the amplitude of 52 mm, the target sizes as a function of IDs were 16, 8, 4, 2, and 1 pixel. For the amplitude of 76.2 mm, the target sizes as a function of IDs were 24, 12, 6, 3, 1 pixel.

2.5. Cardiovascular measures and analyses

2.6.1. Measures. Cardiovascular measures (pre-ejection period [PEP]; heart rate [HR]) were extracted through the Biopac MP160 system at 2000 Hz. The ECG electrodes were put on the right and left shoulder and down to the end of the coasts (Lead II position; see Berntson et al., 2004). The ICG electrodes were placed on the right and left sides of the base of the participant's neck and on the left and right middle axillary line at the height of the xiphoid. Arterial pressure (SBP, DBP, in millimeters of mercury [mmHg]) was measured with a digital automatic blood pressure monitor (OMRON-MIT Elite). The blood pressure cuff was placed over the brachial

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artery above the elbow of the participant's non-dominant arm. We used the Acqknowledge 5.0 software to analyze the PEP (in milliseconds [ms]) and HR (in beats per minute [bpm]) signals. PEP was defined as the time interval between R-onset and B-point (Berntson et al., 2004). The R-onset and the B-point were automatically scored. The B-point location was estimated based on the location of R and C point according to polynomial equation (Lozano et al., 2007), visually inspected and, if necessary, corrected (Sherwood et al., 1990).

2.6.2. Rest period. The rest period lasted eight minutes. PEP and HR were continuously recorded and averaged for each minute, resulting in eight means. Eight SBP and DBP arterial pressure measures were taken at one-minute intervals, resulting in eight measures. For each cardiovascular measure, the baseline score was averaged over three successive lowest means (i.e., PEP and HR) or measures (i.e., SBP and DBP). Each baseline score had a high internal consistency (Cronbach's α values were .97 for PEP, .99 for HR, .96 for SBP, and .82 for DBP).

2.6.3. Task. The experimental task lasted 15 minutes. During this period, PEP and HR were continuously recorded and averaged for each minute, resulting in 15 means. Arterial pressure measures (SBP and DBP) were recorded after every 50-trial block during the experimental task (50th, 100th, 150th), resulting in three measures. Cardiovascular measures during the experimental task had high internal consistency (Cronbach's α values were .98 for PEP, .99 for HR, .96 for SBP, and .94 for DBP). The cardiovascular scores were the mean of all measures recorded during the experimental task.

2.6.4. Cardiovascular reactivity. Cardiovascular reactivity values for PEP, HR, SBP, and DBP were calculated by subtracting the baseline scores of the rest period from the experimental task scores (Llabre et al., 1991).

2.6. Behavioral measures

According to Hoffmann (2011) and Mallat et al. (2019), we focused our behavioral measures on error rate (in percentage [%]) and movement time (MT, in milliseconds [ms]). MT represented the time to click on the target once the movement has been initiated. We analyzed only the correct

responses of MTs. At the impossible level, the error rate was of 100%, and no MT could be analyzed.

2.7. *Subjective measures*

To measure perceived difficulty, we referred to the French version of Eccles and Wigfield's (1995) scale (Capa et al., 2008a, 2008b). This scale has good psychometric properties and contains 4 items such as "How difficult is this task for you?" The participant responded on a Likert scale ranging from 1 (very easy) to 5 (impossible).

2.8. *Statistical analysis*

In agreement with our cardiovascular hypotheses, the curvilinear effect of task difficulty on PEP reactivity score was analyzed with a curvilinear polynomial contrast in the with and without time pressure conditions. Quadratic contrast weights were 2, -1, -2, -1, 2 for the difficulty levels from very easy to impossible. To test the effect of time pressure on physiological adaptability at the very difficult level, we performed one-way ANOVA on cardiovascular reactivity between both conditions of time pressure.

Concerning behavior analyses, the error rate was analyzed with linear contrasts for both conditions of time pressure. Linear contrast weights were -2, -1, 0, 1, 2 for the difficulty levels from very easy to impossible. Furthermore, the linear effect of task difficulty on MT without time pressure was tested with a linear polynomial contrast. Linear contrast weights were -3, -1, 1, 3 for the difficulty levels from very easy to very difficult. However, we tested the curvilinear effect of task difficulty on MT in the condition with time pressure using curvilinear polynomial contrasts. Quadratic contrast weights were 1, -1, -1, 1 for the difficulty levels from very easy to very difficult. To test more directly the effect of time pressure on behavioral adaptability at the very difficult level, we performed a one-way ANOVA on MT between both conditions of time pressure.

3. Results

3.1. *Cardiovascular results*

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3.1.1. Cardiovascular baseline. For each cardiovascular baseline score, we examined potential differences between groups with separate ANOVAs (5 difficulty levels \times 2 time pressure conditions). The results indicated no significant differences (all p s $>$.23). Means and standard errors of baseline scores are reported in Table 1.

3.1.2. Cardiovascular reactivity. The quadratic contrasts of task difficulty on PEP reactivity score were significant in the condition with time pressure, $F(1,120) = 7.91, p < .01, \eta_p^2 = .06$, and the condition without time pressure, $F(1,120) = 9.61, p < .01, \eta_p^2 = .07$, and captured all significant variance in both conditions of time pressure (all residuals, $F < 1$). As expected, in both conditions, PEP reactivity was high at the intermediate level ($M = -6.13, SE = 3.17$ for the time pressure condition, and $M = -4.01, SE = 1.48$ for the without time pressure condition) and low in the other conditions of difficulty in the time pressure condition ($M = -0.67, SE = 1.44$ for very easy; $M = -0.48, SE = 0.80$ for easy; $M = -3.46, SE = 1.51$ for very difficult; $M = 1.94, SE = 0.87$ for impossible) and in the without time pressure condition ($M = -1.21, SE = 1.68$ for very easy; $M = 0.58, SE = 1.37$ for easy; $M = 1.67, SE = 1.48$ for very difficult; $M = -0.53, SE = 0.86$ for impossible) (Fig. 3).

Table 1

Means and standard errors in parentheses of cardiovascular baseline scores according to the groups of task difficulty and time pressure.

Task difficulty	Time pressure	PEP (ms)	HR (bpm)	SBP (mmHg)	DBP (mmHg)
Very easy	With	109.87 (1.85)	79.11 (2.54)	111.90 (1.97)	75.22 (1.74)
	Without	109.71 (2.92)	79.87 (2.02)	107.62 (2.07)	62.56 (1.62)
Easy	With	108.13 (1.72)	76.53 (2.47)	113.42 (1.68)	75.02 (1.71)
	Without	108.18 (1.65)	77.09 (1.66)	112.32 (2.46)	62.62 (1.35)
Intermediate	With	111.48 (2.11)	76.99 (3.33)	112.26 (2.15)	72.63 (1.45)
	Without	110.21 (1.92)	76.70 (2.10)	110.61 (1.88)	62.67 (1.02)
Very difficult	With	112.18 (2.17)	80.79 (2.59)	112.97 (2.57)	75.72 (3.04)
	Without	108.92 (2.73)	76.82 (1.82)	109.91 (2.21)	61.92 (1.28)
Impossible	With	108.25 (2.05)	76.10 (2.63)	112.93 (1.59)	73.06 (1.67)
	Without	107.23 (1.42)	73.47 (2.19)	110.15 (1.80)	62.00 (1.16)

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Note. $N = 25$ for all cells. PEP: pre-ejection period, HR: heart rate, SBP: systolic blood pressure, DBP: diastolic blood pressure. Pre-ejection period was in milliseconds (ms) and heart rate was in beats per minute (bpm). Systolic blood pressure and diastolic blood pressure were in millimeters of mercury (mmHg).

As expected, one-way ANOVA revealed a significant difference in PEP reactivity score between condition of time pressure at the very difficult level, $F(1,48) = 7.19, p < .01, \eta_p^2 = .13$. PEP reactivity score at the very difficult level was higher ($M = -3.46$ ms, $SE = 1.51$) in the condition with time pressure compared to the without time pressure condition ($M = 1.67$ ms, $SE = 1.18$) (Fig. 3).

The effect on HR, SBP, DBP reactivity was non-significant (all p s $> .47$).

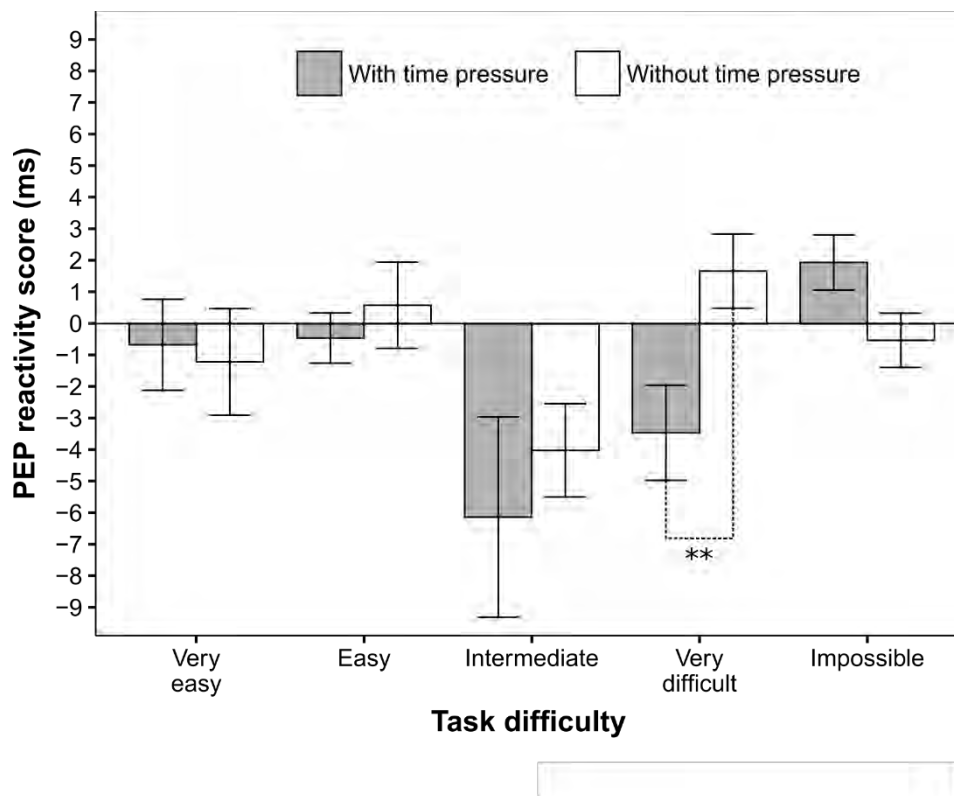


Fig. 3. Mean PEP reactivity scores (milliseconds) according to task difficulty with or without time pressure. Error bars represent standard error. ** $p < .01$.

3.2. Behavioral results

3.2.1. Error rate. A significant linear contrast of task difficulty on error rate was found in the condition with time pressure ($F(1,120) = 1120.86, p < .001, \eta_p^2 = .90$) and in the condition without

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time pressure ($F(1,120) = 901.46, p < .001, \eta_p^2 = .88$). In both cases, linear contrasts captured all significant variance (residuals, $F < 1$). Error rate increased gradually with the task difficulty in both conditions (Fig. 4). In the time pressure condition, means (standard errors) were $M = 11.28$ (2.26) for very easy, $M = 25.71$ (3.20) for easy, $M = 53.97$ (3.17) for intermediate, $M = 82.43$ (2.24) for very difficult, and $M = 100$ (0) for impossible. In the without time pressure condition, means and standard errors were $M = 19.08$ (2.31) for very easy, $M = 27.36$ (1.95) for easy, $M = 50.59$ (2.82) for intermediate, $M = 77.42$ (1.71) for very difficult, and $M = 100$ (0) for impossible.

3.2.2. *MT*. In the time pressure condition, the quadratic contrast of task difficulty on MT was significant, $F(1,96) = 10.53, p < .002, \eta_p^2 = .10$, and captured all significant variance (residual, $F < 1$). Means and standard errors were $M = 1294.40, SE = 56.18$ for very easy, $M = 1340.13, SE = 42.98$ for easy, $M = 1376.29, SE = 52.49$ for intermediate, and $M = 1120, SE = 30.03$ for very difficult (Fig. 4).

In the condition without time pressure, a significant linear contrast of task difficulty on MT was found, $F(1,96) = 12.26, p < .001, \eta_p^2 = .11$, and captured all significant variance (residual, $F < 1$). Means and standard errors were $M = 1919.38, SE = 41.49$ for very easy, $M = 2026.14, SE = 31.59$ for easy, $M = 2025.06, SE = 27.19$ for intermediate, and $M = 2086.64, SE = 25.09$ for very difficult (Fig. 4).

As expected, the one-way ANOVA revealed a significant difference in MT between conditions of time pressure and without time pressure at the very difficult level, ($F(1,48) = 578.01, p < .001, \eta_p^2 = .92$). MT was faster at the very difficult level in the condition with time pressure compared to the without time pressure condition. This difference in MT between conditions of time pressure seemed most important at the very difficult level compared to the other conditions (Fig. 4). To address this issue, we performed a complementary two-way ANOVA (5 difficulty levels \times 2 time pressure conditions). Results revealed an interactive effect between task difficulty and time pressure, $F(3,96) = 7.72, p < .001, \eta_p^2 = .23$. MT was shorter in the time pressure than in the without time pressure condition, particularly at the very difficult level.

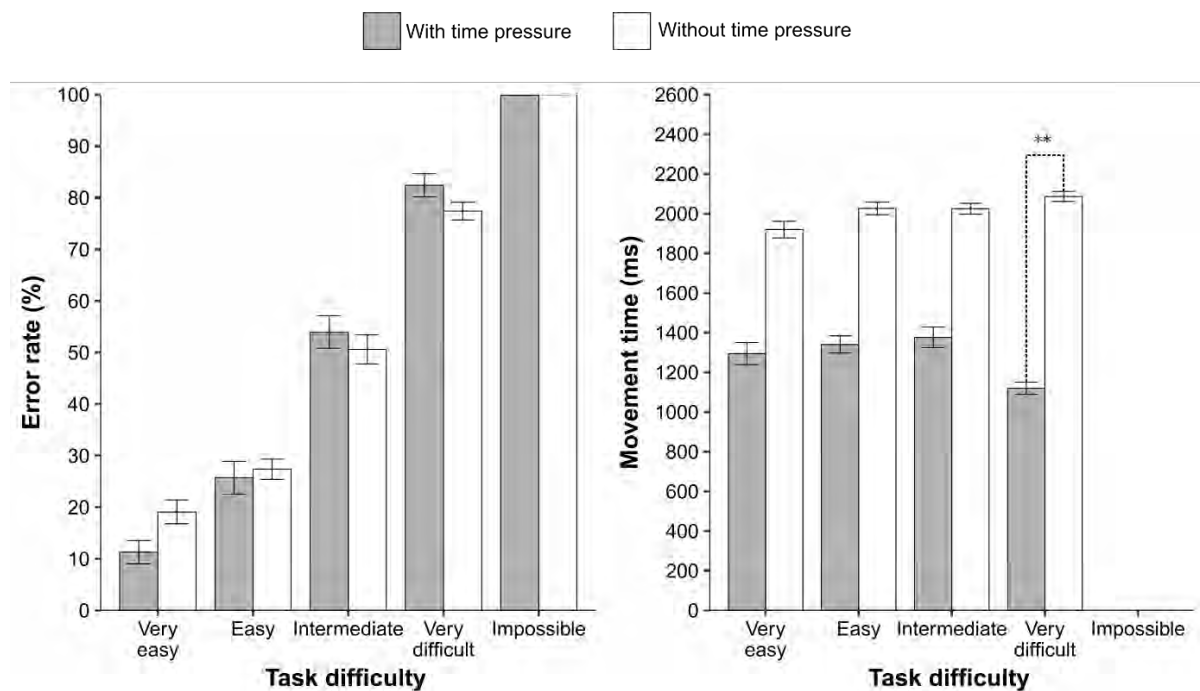


Fig. 4. Means of error rate (percentage) and movement time (milliseconds), according to task difficulty with or without time pressure. Error bars represent standard error. $**p < .01$.

3.3. Subjective results

The ANOVA (5 difficulty levels \times 2 time pressure conditions) revealed a significant effect of task difficulty on perceived difficulty score, $F(4,120) = 27.45, p < .001, \eta_p^2 = .74$. Perceived difficulty score increased across difficulty levels. Means and standard errors were $M = 2.18, SE = .10$ for very easy level, $M = 2.30, SE = .13$ for easy level, $M = 2.48, SE = .12$ for intermediate level, $M = 2.64, SE = .13$ for very difficult level, and $M = 3.46, SE = .17$ for impossible level. No other effect was found ($ps > .16$).

4. Discussion

In this study, we investigated whether time pressure encouraged the curvilinear relationship of mental workload on behavioral and physiological adaptability, postulated by Hancock and Szalma (2006) (Fig. 1) and experimentally demonstrated by Mallat et al. (2019). Time pressure should be an important factor in behavioral and physiological adaptability when task demand exceeds the intermediate (i.e., very difficult) level. If the behavioral and physiological adaptability is encouraged

by time pressure, then we should observe a higher PEP reactivity and faster MT for the condition of time pressure compared to the without time pressure condition at the very difficult level.

4.1. *Manipulation of mental workload*

Error rate and perceived difficulty scores increased across the five levels of task demand in both conditions of time pressure. In agreement with the calculated level of difficulty based on Fitts' law in both conditions of time pressure, these results suggest a successful experimental manipulation of mental workload.

4.2. *Curvilinear effect of mental workload on physiological adaptability*

The results of PEP reactivity supported the curvilinear hypothesis of Hancock and Szalma (2006). We observed a significant curvilinear effect of mental workload on PEP reactivity in both conditions of time pressure (Fig. 3). For each condition, PEP reactivity scores were high at intermediate level and low at other levels of task demand. However, the effects of task difficulty on heart rate and blood pressure were not significant. This result is not surprising, since PEP is a purer index of beta-adrenergic influence on the heart. Nevertheless, in this experiment, heart rate and blood pressure were stable. This confirmed the association between the beta-adrenergic effect and PEP score, and we can conclude that any changes of PEP reactivity reflected mental effort mobilization (Kelsey, 2012; Wright, 1996). These results confirmed the curvilinear effect of mental workload on physiological adaptability in the time pressure condition (Mallat et al., 2019) and extended it to the without time pressure condition.

Most interestingly, the present study provided the first evidence that time pressure encouraged behavioral and physiological adaptability (Hancock and Szalma, 2006).

4.3. *Time pressure modulates the curvilinear effect of mental workload on behavioral and physiological adaptability*

A linear effect of task difficulty on error rate was observed in both conditions of time pressure (Fig. 4). However, a curvilinear effect of task difficulty on MTs was observed only in the time pressure condition. For the time pressure condition, these behavioral results coupled with the

physiological results suggested that participants invested more mental effort to compensate for the decline in performance and to cope with the increase in task difficulty. When task approached overload (i.e., the very difficult level), the error rate continued to increase but MT decreased. Complementarily, a decrease in PEP reactivity scores was observed at the very difficult level. This suggested that participants mobilized less mental effort and we interpreted this speed-accuracy trade-off as a disengagement. Above an intermediate level of difficulty (i.e., overload), participants decreased mental effort investment by using a behavioral strategy. Participants should have perceived a low probability to attain the target and changed the strategy to move faster to the targets (Hoffmann, 2011; Hoffmann et al., 2013). In fact, a curvilinear effect of mental workload on behavioral and physiological adaptability was observed in the time pressure condition.

Most interestingly, this behavioral and physiological adaptability was encouraged by time pressure. To address this issue, we compared the two conditions of time pressure in terms of the behavioral and physiological adaptability at the very difficult level. Participants had higher PEP reactivity scores and faster MTs in the time pressure than in the without time pressure condition. In the condition of very difficult level and without time pressure, error rate and MTs increased linearly. Taken together, these results suggested that participants in the without time pressure condition disengaged but without a change in behavioral and of physiological adaptability. The change in behavioral and physiological adaptability was observed only in the time pressure condition when task demand approached overload. In agreement with the model of Hancock and Szalma (2006), time pressure modulated a curvilinear effect of mental workload on behavioral and physiological adaptability when the mental workload is high.

4.4. Curvilinear or linear effect of task demand on mental effort

Mental effort mobilization is often conceptualized as a linear function of subjective task demand (MIT, Brehm and Self, 1989). This linear relationship between perceived difficulty and mental effort, which is activated as long as success is possible and justified, was highlighted in several studies using cardiovascular measures and PEP reactivity (see Richter et al., 2016; Wright

and Kirby, 2001 for reviews). In contrast to these studies, this study supports a curvilinear relationship with a higher level of effort mobilization at the intermediate level of task difficulty. Studies using the MIT predict an inverted v-shaped function with a higher level of effort mobilization at a very difficult level. We assumed that this difference stems from potential differences between levels of difficulty in the subjective effort-value association. The effort is both costly and valued (Inzlicht, Shenhav, and Olivola, 2018). However, the amount of effort mobilized is a potential moderator of the subjective effort-value association, and a negative correlation could be observed between subjective difficulty and value (Eccles and Wigfield, 1995). Any tasks that require further effort beyond this limit are devalued. In agreement with the MIT, individuals are only willing to exert their efforts to a limit, referred to as the level of maximally justified effort. In the present study, participants may have invested mental effort as a function of subjective difficulty until the intermediate level. However, above this level, the limit of maximally justified effort has probably decreased, resulting in a progressive disengagement and a curvilinear effect. To address this issue, further studies should contrast the subjective value with difficulty.

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ARTICLE 3

Running head: Mental Workload, Complexity, and Pre-Ejection Period

MENTAL WORKLOAD EFFECT ON BEHAVIORAL AND PHYSIOLOGICAL ADAPTABILITY IN AIR TRAFFIC CONTROL TASK: A CARDIOVASCULAR APPROACH

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Précis/Short abstract: The article provides the first demonstration of a cognitive trade-off between performance and effort in an ATC task with curvilinear effect of task complexity on operator behavioral and physiological adaptability.

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Mental workload effect on behavioural and physiological adaptability in air traffic control task: a cardiovascular approach

Objective: We tested a cognitive tradeoff resulting from a behavioral and physiological adaptability in ATC task with a cardiovascular measure.

Background: In the ATC literature, several authors have highlighted the presence of cognitive tradeoff. More precisely, the authors explain that strategies allow operators to adapt their performance and effort to regulate their mental workload. Mallat, Cegarra, Calmettes and Capa (2019) have highlighted this adaptability through a curvilinear effect of mental workload on behavioral and physiological adaptability initially postulated by Hancock and Szalma (2006). However, this demonstration was done with a modified Fitt's task.

Method: An air traffic control-microworld (LABY) was used. Participants were asked to guide one or more aircraft through a predetermined flight path. Five levels of complexity were determined (very easy, easy, intermediate, very complex, impossible). Behavioral and physiological adaptability was indexed by the performance (RT, accuracy, flight path deviation) and PEP reactivity.

Results: A curvilinear effect of task complexity on PEP and RT was significant. A decline in performance was found up to the intermediate level with a maximum PEP reactivity. At the very complex level, a performance-effort tradeoff was observed with less effort mobilization and shorter response time to guarantee a certain performance.

Conclusion: We demonstrate that ATC tasks are likely to activate a performance-effort tradeoff with a behavioral and physiological adaptability of the operator.

Application: The results are important for the modeling of mental workload, particularly in a performance-sensitive domain as ATC. They can help guide the design to maximize an optimal mental workload.

Keywords: Mental workload, Complexity, Performance, Effort, Cardiovascular reactivity

INTRODUCTION

In complex work systems, operators must adapt their decision making and performance to dynamic, ever-changing environments, concurrent task demands, time pressure, and tactical constraints (Loft, Sanderson, Neal, & Mooij, 2007). The assessment and prediction of mental workload associated with complex work systems has long been recognized as a central issue (e.g., Moray, 1979). Mental workload is a multidimensional construct that is determined by the task demand, the operator, and the environment (Hart & Staveland, 1988; Wickens, 2008). The task demand may differ with the task complexity imposed on the operator (Gopher & Donchin, 1986).

Complexity in ATC

Task complexity is defined as the number of variables to be controlled and their interactions (Funke, 2001; Leplat, 1988). There are many complex tasks, such as air traffic control (ATC). Several factors contribute to ATC complexity, such as airspace structure and traffic. Airspace structural complexity may consist of sector shape, crossing points and small-angle convergence routes (Christien, Benkouar, Chaboud, & Loubieres, 2002; Nunes & Scholl, 2005). Moreover, traffic complexity may be defined in terms of density (Chatterji & Sridhar, 2001; Loft et al., 2007) and elements relating to the change of state of the aircraft such as changes in altitude, flight path (Boag, Neal, Loft, & Halford, 2006).

Many studies have experimented ATC complexity through simulated environments, microworlds in laboratory (Boag, Strickland, Heathcote, Neal, & Loft, 2019; Brookings, Wilson, & Swain, 1996; Giraudet, Imbert, Tremblay, & Causse, 2015; Imbert, Hodgetts, Parise, Vachon, & Tremblay, 2014; Kopardekar, Schwartz, Magyarits, & Rhodes, 2007; Loft, Hill, Neal, Humphreys, & Yeo, 2004; Metzger & Parasuraman, 2005). Furthermore, traffic complexity is an indicator most frequently used as a predictor of task demand. Traffic complexity influences the controller by increasing task demand, which may lead to poor performance (Durso & Manning, 2008). However, increases in traffic do not always lead to increases in task demand and decreases in performance

(Cummings & Guerlain, 2007). As task demand increases, controllers adapt and change their operative methods (Spérando, 1971, 1978).

Controller Adaptability in ATC

According to Spérando (1971), mental workload is not something imposed upon a passive operator. Instead, it is something the operator actively manages. The author proposed a model in which changes in strategies allow an operator to manage the cognitive tradeoff between performance and effort. More precisely, strategies allow operator to adapt their performance and effort to regulate their mental workload, thus keeping it within acceptable limits (Athènes, Averty, Puechmorel, Delahaye, & Collet, 2002; Averty, Collet, Dittmar, Athènes, & Vernet-Maury, 2004; Cullen, 1999; Hilburn, 2004; Histon et al., 2002; Majumdar, Ochieng, McAuley, Lenzi, & Lepadatu, 2004; Nunes & Mogford, 2003).

One way to manage high workload is to make an adaptive strategy or strategy shift. The operator might resort to a less strenuous strategy to perform the task. In general, the chosen strategy depends on three factors: individual characteristics (e.g., training, motivation, age), task characteristics (e.g., its requirements, including work conditions) and workload (Spérando 1971). For example, Spérando expects a heavy mental workload to produce a speed-accuracy tradeoff. Reaction time and accuracy are inversely related, so as speed increases there usually is a decrease in task accuracy. The tradeoff is said to occur when fast reaction times are accompanied by high error rates.

Some authors postulate that controllers would actively maintain this performance-effort tradeoff (Averty, Athènes, Collet, & Dittmar, 2002; Averty et al., 2004). Averty et al. (2002, 2004) with the Task Load Index (TLI) model defines the operator's actions as the way to regulate their mental workload. The authors highlight the maturing-time phenomenon implemented by controllers. In other words, workload adaptability rests on the interval of time between a diagnosis of action, and the moment when a definite solving action is undertaken. Modulation of the length

of this interval is the mechanism through which controllers can regulate their workload. This time interval has been called the *maturing time*. A short maturing time refers to actions undertaken at the outset of the diagnosis that keeps workload at the lowest permissible level for a given problem, whereas a longer maturing time increases the attentional demand, thereby increasing workload. However, increasing maturing time also decreases the uncertainty upon which a decision to intervene has to be made. Moreover, the later a resolution is undertaken, the more adequate it will be (for example, better precision for flight path modification). This leads to a tradeoff between uncertainty and time pressure: elapsing time decreases the uncertainty but increases the pressure. A balance has to be maintained, according to performance and effort.

However, there is no empirical demonstration that shows a cognitive tradeoff activation between performance and effort in ATC tasks.

Mental workload, behavioral and physiological adaptability

In cognitive ergonomics, Hancock and colleagues considered a curvilinear effect of mental workload on behavioral and physiological adaptability (Hancock & Caird, 1993; Hancock & Chignell, 1988; Hancock & Szalma, 2006, 2008; Hancock & Warm, 1989; Young, Brookhuis, Wickens, & Hancock, 2015). More precisely, behavioral and physiological adaptability varies by stress level (Figure 1). Hancock and Szalma (2006) considered task demand as the primary source of stress for an operator. Faced with the effects of task demand, operators regulate their activity with adaptive processes depending on the response strategies of a number of body structures. The task demand level can vary (i.e., hypostress for very low task demand and hyperstress for very high task demand) of underload to overload tasks. The underload zone is known to lead the insufficient stimulation and decreased performance (Brookhuis, De Waard, & Fairclough, 2003; Hancock, 2013). Conversely, the overload zone, the task demand is too high, implying the loss of control of the situation and decreased task performance (Cegarra & Chevalier, 2008).

From the low level up to the intermediate level of task demand, increased behavioral and physiological adaptability, the operator adapts effort mobilization to protect performance or reduce the decline in performance.

According to Hancock and Szalma's model (2006), when task demand exceeds the intermediate level, the cognitive cost can be minimized by adaptive strategies. These strategies should protect individuals from excessive costs and prevent them from engaging in a costly activity, guarantee a certain performance.

At the center of curvilinear effect, the intermediate level, or comfort zone, the task demand is optimal, and behavioral and physiological adaptability is stable. The operator achieves satisfactory performance at an acceptable cost. A balance is maintained, according to performance and effort.

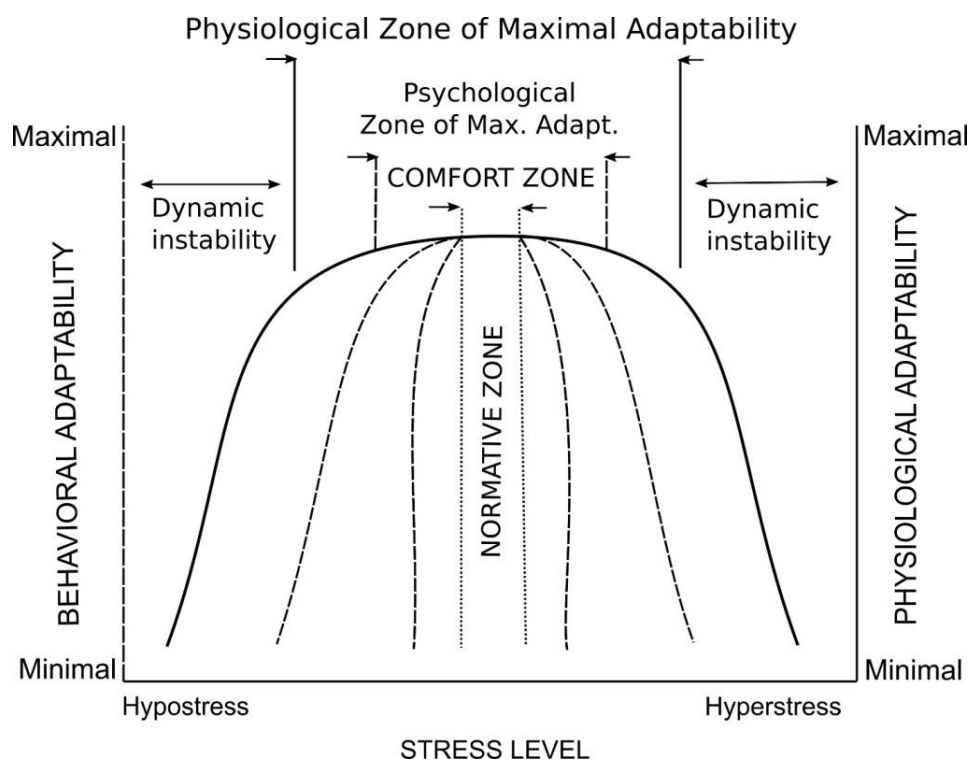


Figure 1. Curvilinear model of the effect of stress level on behavioral and physiological adaptability. The primary source of stress is task demand. Adapted from "Stress and Neuroergonomics" by P.A. Hancock, and J. L. Szalma, 2006, p. 158.

The mental workload model of Hancock and Szalma (2006) has been globally validated by Mallat, Cegarra, Calmettes, and Capa (2019). The authors showed a curvilinear effect of task difficulty through a modified Fitts' task (Hancock & Caird, 1993) on behavioral adaptability by performances measure (Movement Time [MT]) and physiological adaptability with cardiovascular approach of mental effort (Pre-Ejection Period [PEP]).

Physiological measurement

Physiological measures are frequently used to indicate the amount of mental effort associated with a task (Marinescu et al., 2018; Schwalm, Keinath, & Zimmer, 2008; Vicente, Thornton, & Moray, 1987; Young et al., 2015). The most common physiological measures used in ATC are electroencephalogram EEG/ERP (Aricò et al., 2016; Giraudet, Imbert, Bérenger, Tremblay, & Causse, 2015), eye tracking (Ahlstrom & Friedman-Berg, 2006; Hilburn, 1999; Mallis & Dinges, 2004; Wilson & Russell, 2003) and cardiovascular measures (Brookings, Wilson, & Swain, 1996; Collet, Averty, & Dittmar, 2009).

Recent research on cardiovascular reactivity related to mental effort has highlighted PEP (Framorando & Gendolla, 2019; Freydefont, Gollwitzer, & Oettingen, 2016; Mallat et al., 2019; Silvestrini, 2017). Berntson, Lozano, Chen, and Cacioppo (2004) define PEP as the time interval between beginning of the excitation of the left ventricle and the opening of the aortic valve. PEP is a pure index of beta-adrenergic sympathetic (Benschop et al., 1994; Richter, Gendolla, & Wright, 2016). Systolic blood pressure (SBP) and diastolic blood pressure (DBP) are also determined by peripheral vascular resistance (Levick, 2003, 2013). The changes in myocardial contractility force are a direct indicator of PEP (Newlin & Levenson, 1979; Sherwood, Dolan, & Light, 1990). PEP decreases when myocardial contraction increases. Other cardiovascular measures, such as heart rate (HR), are measures of mental effort (e.g., Capa, Audiffren, Ragot, 2008; Dehais et al., 2014). However, HR is determined by sympathetic and parasympathetic activation and is not a reliable index of mental investment. Increases in HR may be caused by increased sympathetic activity but

can also be the result of decreased parasympathetic activity. Still, to check a possible pre- or after-load effects, PEP should be measured with blood pressure and HR (Sherwood et al., 1990).

Hypothesis

We wondered if the ATC tasks really permit a cognitive tradeoff activation between performance and effort with operator behavioral and physiological adaptability. More precisely, we hypothesize that, when task demand increases from the very low up to the intermediate level, then a stronger mental effort should occur to reduce the decline in performance. We expected to observe this decline (i.e., an increase of accuracy, number of flight path deviations and Response Time [RT]) as well as a stronger PEP reactivity related to the mental effort. Still, beyond the intermediate level, the behavioral and physiological adaptability decreases, we should see an implementation of behavioral adaptive strategies to protect operators from large or excessive costs and guarantee a certain performance. This decrease in behavioral and physiological adaptability would induce a higher accuracy and flight path deviation, and lower PEP reactivity related to the mental effort. Behavioral adaptive strategy should be on RT (Imbert, Hodgetts, Parise, Vachon, & Tremblay, 2014). In accordance with previous studies (Hoffmann, 2011; Mallat et al., 2019; Spérando, 1971), we should find a speed-accuracy tradeoff on RT in very complex level (after the intermediate level, but before overload). When task demand increases from very low up to the intermediate level, then a stronger mental effort should occur to reduce the decline in performance. We expected to observe this decline (i.e., an increase of accuracy, flight path deviation and RT) as well as a stronger PEP reactivity related to the mental effort.

To sum up, we postulated a curvilinear effect of task demand on PEP reactivity, with high PEP reactivity at the intermediate level of task demand and low PEP reactivity at other levels. Concerning the behavioral aspect, we proposed a linear effect of task demand on the accuracy and number of flight path deviation. We hypothesize a curvilinear effect of task demand on RT, with

increase up to the intermediate level and then a decrease. In fact, we expected to observe a speed-accuracy tradeoff when task demand exceeds the intermediate level.

METHOD

Participants

One hundred participants from the National University Institute Champollion were recruited for the experiment. All were between 18 and 30 years old. None had a history of mental, cognitive, cardiac or neurological disorder, substance abuse, or taking psychoactive medications. They all received information about the experimental procedure and signed an informed consent. They were randomly assigned to one of five levels of task complexity (very easy, easy, intermediate, very complex, impossible). The distribution of women and men was balanced between experimental conditions with 15 women and five men on each level.

Aircraft guiding task

Laby microworld is a functional simulation of ATC (Imbert et al., 2014). The task goal consists in guiding one or more aircraft through a predetermined flight path, indicated by a green path (Figure. 2). A deviation in the assigned path set off a visual alert on the screen until the aircraft returned to the path (Figure. 2). The task ended as soon as the first aircraft reached the arrival red area at the end of the path, maintaining the same level of complexity along the task with the same number of aircraft. Participants had to change flight path and altitude as quickly and accurately as possible. Their instructions (flight path, altitude) were sent via a pop-up window on each aircraft that provided a drop-down menu to select from available options (Figure. 3).

Participants had to adjust altitude instructions before the aircraft passed the black bar on path (Figure. 3b). If altitude instructions were incorrect or absent, performance would deteriorate. Moreover, if the aircraft deviates from the assigned path and altitude instructions are not presented, performance again would deteriorate. If more participants stayed in the path and immediately

informs the altitude instructions, performance will improve.



Figure 2. A scenario with one aircraft. The top left corner displays a compass rose to help participants choose the aircraft flight path. On the bottom right a visual alert was displayed due to an aircraft leaving the flight path.

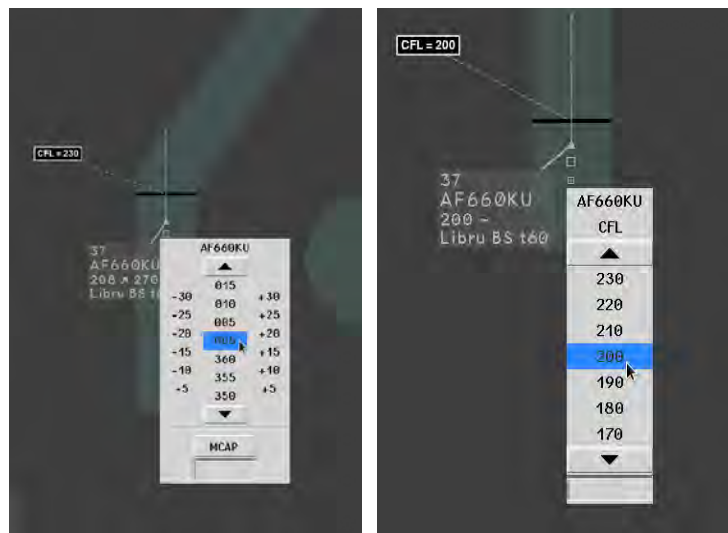


Figure 3. The window used to select the aircraft flight path, which appeared when clicking on the aircraft's label (3a). The altitude was symbolized by a black bar with a label named Cleared Flight Level (CFL). The window used to select the aircraft altitude before the aircraft passes the black bar on path (3b).

Experimental design

According to our predictions on mental workload and adaptability through different levels of task demand (Hancock & Caird, 1993; Hancock & Szalma, 2006; Mallat et al., 2019). Laby microworld declined in all five levels of complexity. To ascertain that the levels of complexity produce a linear decrement in performance, we conducted a pre-test on 10 participants. In this pre-test, we manipulated Laby's parameters by changing the number of aircraft. We found that the number of aircraft influences the amount of instructions to emit on both the flight path and altitude. Following the pre-test, five levels ranging from very easy to impossible were validated. The very easy level was composed of one aircraft, 49 altitude instructions and five turns in the path; on the easy level there were two aircraft, 96 altitude instructions and 10 turns; on the intermediate level there were three aircraft, 144 altitude instructions and 15 turns; on the very complex level, four aircraft, 174 altitude instructions and 17 turns on the very complex level and on the impossible level, five aircraft, 222 altitude instructions, 22 turns.

Cardiovascular measures

Pre-ejection period [PEP]; heart rate [HR]; systolic blood pressure [SBP]; diastolic blood pressure [DBP] were collected during a rest period (8 minutes) and task (9 minutes). PEP (in milliseconds [ms]) and HR (in beats per minute [bpm]) were measured continuously using a Biopac MP160 system that sampled electrocardiogram (ECG) and thoracic impedance cardiogram (ICG) signals at 2000 Hz. For the ECG, three electrodes were placed on the right and left shoulder and down to the end of the coasts (Lead II position; see Bernston et al., 2004). For the ICG, electrodes were placed on the right and left sides of the base of participants' neck and on the left and right middle axillary line at the height of the xiphoid. A digital automatic blood pressure monitor (CARESCOPE V100) was used to measure arterial pressure (SBP and DBP) in millimeters of mercury (mmHg). The blood pressure cuff was placed over brachial artery above the elbow of the participants' non-dominant arm and was automatically inflated at 1-min intervals. All

cardiovascular measures and signals were recorded directly on computer. Neither the participant nor the experimenter were aware of the values during the experiment.

The PEP and HR signals were analyzed with the Acqknowledge 5.0 software. PEP was determined as the time interval (ms) between R-onset and B-point (Berntson et al., 2004). The R-onset and the B-point were automatically scored for each artifact-free ensemble average. The B-point location was estimated based on locations of R and C points according to polynomial equation proposed by Lozano et al. (2007), visually inspected and corrected, if necessary, as recommended by Sherwood et al. (1990). For the rest period, PEP and HR measures were averaged over 1-min intervals. PEP and HR baseline scores were calculated based on the mean of two non-significantly different successive measures. During the experimental task, PEP and HR scores were the arithmetic means of all measures obtained during task.

Arterial pressure (SBP and DBP) was measured at 1-min intervals during the rest period and every 3 min during task. All cardiovascular reactivity scores were computed for each participant and each cardiovascular measure. Each cardiovascular reactivity score was calculated by subtracting the baseline scores (i.e., cardiovascular activity during the rest period) from the task scores (i.e., cardiovascular activity during the task) (Llabre, Spitzer, Saab, Ironson, & Schneiderman, 1991).

Behavioral measures

Performance was measured by accuracy (in %), response time for altitude instructions (RT, in milliseconds [ms] and flight path deviation (means of numbers). Accuracy was defined as the percentage of altitude instructions informed about the maximum altitude instructions that can be presented. RT was the time from onset of the stimulus and the end of action. Only the RT of correct altitude instructions is taken into account.

Subjective measure

The French version of Eccles and Wigfield's (1995) scale was used to evaluate perceived complexity. This scale has good psychometric properties and is known to be sensitive to differences

in difficulty levels (Capa et al., 2008). It consists of four items: How hard is the task for you? Compared to other students, how hard is the task for you? Compared to everyday tasks, how hard is the task for you? I think this task is? The participant responded on a Likert scale from 1 (very easy) to 5 (impossible).

Procedure

First, participants read and signed the informed consent agreement and answered a few biographical questions (as proposed by Matthews, Altman, Campbell, & Royston, 1990). Next, the ECG and ICG electrodes were placed. The signal was visually verified and validated on the AcqKnowledge software. Second, the participants were set in a rest period. A video of a chimney fire was presented on the computer screen for 8 minutes. Participants had to watch the video and relax. Third, the participants received the task description. They performed a training to the experimental task for 5 minutes. Fourth, they performed the task in one of the five task complexity levels for 9 minutes. At the end they filled out the perceived complexity scale.

Statistical analysis

In accordance with our predictions, we tested a curvilinear effect of task complexity on performance scores and cardiovascular scores.

The curvilinear effect of task complexity on PEP reactivity should be analysed with a curvilinear polynomial contrast. In this way, quadratic contrast weights were 2 for the very easy level, -1 for the easy level, -2 for the intermediate level, -1 for the very complex level, and 2 for the impossible level.

Concerning behavioral analyses, we tested the linear effect of task complexity on accuracy and flight path deviation with a linear polynomial contrast. Linear contrast weights were -2, -1, 0, 1, 2 for the five levels of task complexity.

Next, the curvilinear effect of task complexity on RT was tested with a curvilinear polynomial contrasts. Quadratic contrast weights were 1 for very easy, -1 for easy, -1 for intermediate, 1 for

very complex. As the accuracy in the impossible level would be close to 0 %, very few data would be available for this RT level.

We analysed perceived complexity scores with a one-way ANOVA on the five levels of task complexity.

RESULTS

Cardiovascular results

Cardiovascular baseline

Baseline values (PEP, HR, SBP, DBP) were collected by averaging the 9 minutes of rest period (9 means; all Cronbach's α 's > .91). No differences among levels were found for the rest period ($ps > .31$). Means and standard errors by task complexity are detailed in table 1.

Table 1. Means (Standard Errors) of Cardiovascular Baseline Scores

	Task demand				
	Very easy	Easy	Intermediate	Very complex	Impossible
PEP	109.72 (1.68)	109.42 (2.03)	109.62 (2.55)	108.72 (2.17)	110.75 (2.29)
HR	81.57 (2.25)	78.07 (2.87)	83.97 (2.6)	82.99 (3.12)	80.73 (1.96)
SBP	109.15 (2.05)	109.72 (2.56)	106.33 (2.30)	111 (2.54)	108.70 (1.97)
DBP	64.08 (1.85)	66.11 (2.23)	61.37 (1.17)	65.51 (1.66)	63.33 (1.45)

Note. N = 20 for all cells. PEP: Pre-Ejection Period, HR: Heart Rate, SBP: Systolic Blood Pressure, DBP: Diastolic Blood Pressure. Pre-ejection period was in milliseconds (ms) and heart rate was in beats per minute (bpm). Systolic and diastolic blood pressure were in millimeters of mercury (mmHg).

Cardiovascular reactivity

The quadratic contrast of task complexity on PEP reactivity scores was significant ($F(1,95) = 5.82, p < .05, \eta_p^2 = .06$) and captured all significant variance (residual, $F < 1$). The higher PEP

reactivity score was at intermediate level ($M = -4.45$, $SE = 1.34$) and lower for other levels of task complexity. Means and standard errors were $M = -0.89$, $SE = 0.79$ for very easy; $M = 0.74$, $SE = 1.55$ for easy; $M = -2.12$, $SE = 0.88$ for very complex; $M = 0.92$, $SE = 1.07$ for impossible (see in Figure 4). Decomposing this curvilinear effect through focused comparisons among conditions revealed a significant difference between easy and intermediate ($F(1,38) = 6.40$, $p < .02$, $\eta_p^2 = .14$), intermediate and impossible ($F(1,38) = 9.82$, $p < .01$, $\eta_p^2 = .20$) levels. There was no significant difference among other levels ($p_s > .15$).

No difference in task complexity on HR, SBP and DBP reactivity scores was found ($p_s > .17$).

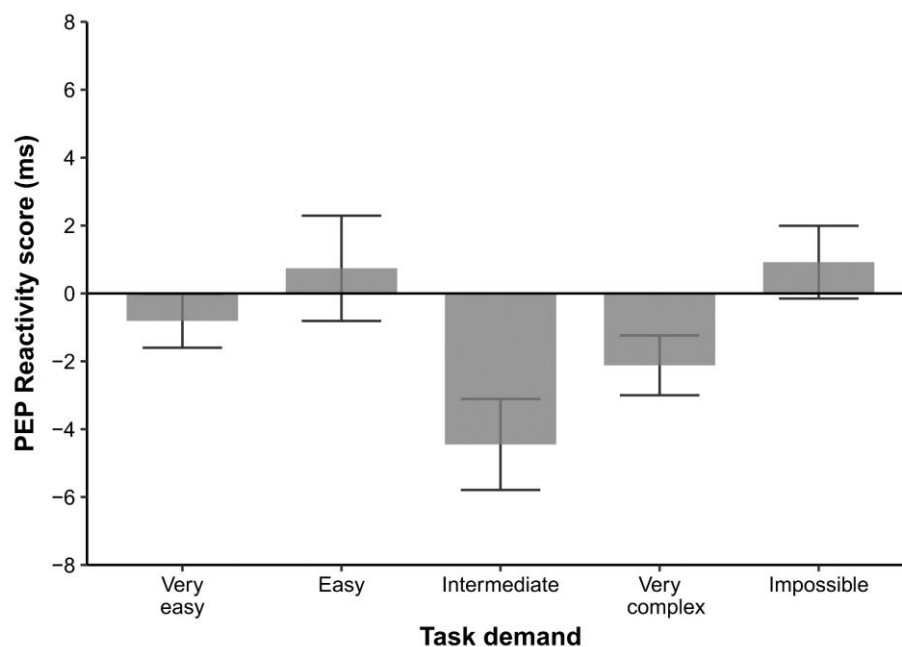


Figure 4. PEP reactivity score means according to task demand.

Behavioral results

The linear contrast of task complexity on accuracy for altitude instructions was significant ($F(1,95) = 603.61$, $p < .001$, $\eta_p^2 = .86$) (residual, $F < 1$). Means and standard errors were $M = 88.25$, $SE = 2.54$ for very easy, $M = 37.87$, $SE = 3.76$ for easy, $M = 19.97$, $SE = 2.92$ for intermediate, $M = 10.95$, $SE = 1.39$ for very complex, and $M = 4.39$, $SE = 0.57$ for impossible (Figure 5). Decomposing this effect by means of one-way ANONAs indicated significant differences across

all conditions ($p_s < .01$ and $\eta_p^2 > .17$).

The quadratic contrast of task complexity on RT for altitude instructions was significant ($F(1,95) = 49.85, p < .001, \eta_p^2 = .34$) (residual, $F < 1$). Means and standard errors were $M = 4.69, SE = .11$ for very easy, $M = 6.13, SE = .12$ for easy, $M = 7.17, SE = .17$ for intermediate, $M = 6.69, SE = .17$ for very complex (Figure 5). Decomposing this linear pattern by means of one-way ANONAs showed significant differences across all conditions ($p_s < .05$ and $\eta_p^2 > .13$).

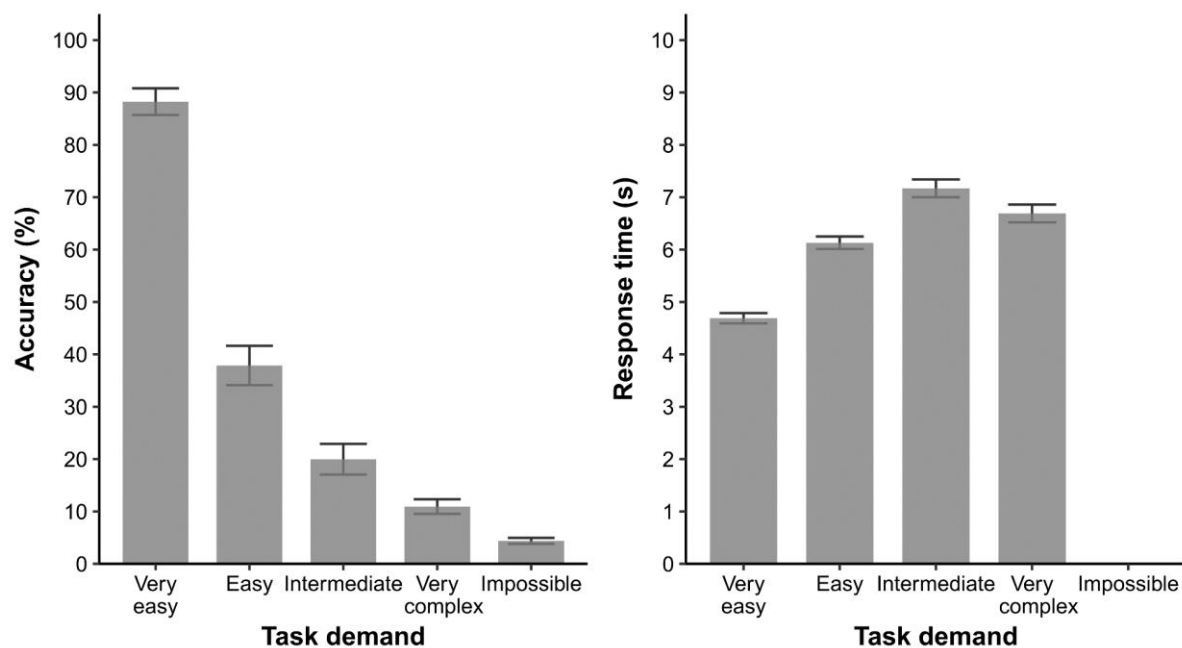


Figure 5. Means of accuracy (%) and RT (s) according to task demand.

The linear contrast of task complexity on flight path deviation was significant ($F(1,95) = 37.76, p < .001, \eta_p^2 = .23$) (residual, $F < 1$). Means and standard errors were $M = 1.25, SE = 0.40$ for very easy, $M = 3.70, SE = 0.90$ for easy, $M = 6.65, SE = 0.93$ for intermediate, $M = 9.65, SE = 1.90$ for very complex, and $M = 11.75, SE = 2.00$ for impossible. Decomposing this effect by means of one-way ANONAs designed significant difference between very easy and easy ($F(1,38) = 6.20, p < .02, \eta_p^2 = .14$), easy and intermediate ($F(1,38) = 5.19, p < .03, \eta_p^2 = .12$) and intermediate and impossible levels ($F(1,38) = 5.35, p < .03, \eta_p^2 = .12$). There was no significant difference among the other levels ($p_s > .14$).

Perceived complexity result

A significant effect of task complexity on the perceived complexity was revealed through one-way ANOVA, $F(4,95) = 27.84, p < .001, \eta_p^2 = .23$. Perceived complexity increased across levels. Means and standard errors were $M = 1.32, SE = .08$ for very easy, $M = 2.03, SE = 0.10$ for easy, $M = 2.34, SE = 0.13$ for intermediate, $M = 2.31, SE = 0.13$ for very complex, and $M = 2.92, SE = 0.17$ for impossible.

DISCUSSION

Manipulation of Mental Workload

The perceived complexity, accuracy and number of flight path deviation increase linearly across the levels of task complexity (very easy, easy, intermediate, very complex, impossible) that is suggest a good experimental manipulation of mental workload.

Behavioral and Physiological Adaptability

The curvilinear effect of mental workload on PEP reactivity was significant (Figure. 4). PEP reactivity scores were high at the intermediate level and low at other levels of task demand. In contrast to PEP reactivity, task demand effects on HR, SBP, and DBP were not significant. However, HR and blood pressure were stable in the present study, we concluded that beta-adrenergic effect caused the present PEP responses, reflecting mental effort mobilization (Wright, 1996). Indeed, PEP reflect increases in beta-adrenergic activity only when HR and blood pressure are stable or increasing (Sherwood et al., 1990).

A curvilinear effect of task complexity on RT was significant (Figure. 5). A decline in performance has been found up to the intermediate level with a maximum PEP reactivity. At the very complex level a performance-effort tradeoff has been observed with less effort mobilization and speed-accuracy tradeoff with shorter RT to guarantee a certain performance.

In agreement with Hancock and Szalma (2006) and Mallat et al. (2019) we found a curvilinear effect of mental workload on behavioral and physiological adaptability.

We empirically demonstrate for the first time that ATC tasks are likely to activate a performance-effort tradeoff with both behavioral and physiological adaptability of the operator. In conformity with Spérandio (1971) controllers regulate their workload by selecting control strategies that meet task demands, driven by the priority of their objectives. The implementation of strategy has a crucial role in task demand management (Loft et al., 2007).

ATC rapidly changes (Eurocontrol, 2007; Federal Aviation Administration, 2005) with an increase in airspace capacity through new decision support tools, increased automation. Faced with the proposed systems, it is essential to assess the mental workload experienced by operators' balance performance with effort, with satisfactory performance and optimal mental workload level.

KEY POINTS

- In ATC several authors assume the presence of cognitive tradeoff between performance and effort. However, these predictions were never empirically demonstrated globally.
- We tested the existence of a cognitive tradeoff resulting from a behavioral and physiological adaptability in ATC tasks with a cardiovascular measure related to mental effort mobilization. We used the pre-ejection period (PEP), an index of beta-adrenergic sympathetic impact.
- The results show the presence of a performance-effort tradeoff with a curvilinear effect of task complexity on performance and effort in ATC task.

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DISCUSSION GENERALE

Ce travail de thèse avait pour objectif de mieux comprendre les effets de la charge mentale de travail sur l'efficacité, notamment sur l'adaptabilité de l'opérateur.

Résumé des résultats expérimentaux

Le premier chapitre empirique et article (Mallat et al., 2019) avait pour objectif de tester le modèle d'efficacité multidimensionnel de Hancock et Szalma (2006), qui postulait un effet curvilinéaire de la charge mentale de travail sur l'adaptabilité comportementale et physiologique. Nous avons observé un effet curvilinéaire de la difficulté de la tâche sur le score de réactivité PEP, avec une mobilisation de l'effort mental plus élevée au niveau intermédiaire que dans les autres niveaux de difficulté, afin de maintenir une charge mentale optimale (Figure 3, p.61). De plus, un effet curvilinéaire de la difficulté de la tâche sur le temps de mouvement a été observé. Une baisse des performances a été notée jusqu'au niveau intermédiaire (taux d'erreur, temps de mouvement), puis au-delà de ce niveau nous avons observé la mise en place d'une stratégie adaptative par l'opérateur à travers un compromis vitesse-précision. L'opérateur était alors plus rapide et moins précis pour garantir une certaine performance (Figure 4, p. 61). Nos résultats ont validé pour la première fois ce modèle curvilinéaire dans sa globalité.

Pour donner suite à ces résultats qui confortent nos choix théoriques et méthodologiques, nous avons testé en accord avec le modèle Hancock et Szalma (2006) si ce n'était pas la pression temporelle présente dans cette tâche et dans de nombreuses situations professionnelles qui favorisait l'adaptabilité comportementale et physiologique. En effet, si nous avons observé une mise en place de stratégie dans le niveau de difficulté le plus élevé, cela l'était dans une tâche avec pression temporelle. Allons-nous retrouver cette adaptabilité dans une tâche sans pression temporelle ?

Le second article avait donc pour objectif de tester si la pression temporelle favorisait l'adaptabilité comportementale et physiologique, avec la mise en place d'une stratégie adaptative.

Nous avons effectivement observé une mobilisation de l'effort mental plus élevée avec pression temporelle que sans pression temporelle à un niveau très difficile de la charge mentale de travail (Figure 3, p.81). Le temps de mouvement était plus court au niveau très difficile avec pression temporelle, que sans pression temporelle (Figure 4, p.83). Nos résultats ont confirmé que la pression temporelle favorise l'adaptabilité comportementale et physiologique avec la mise en place d'une stratégie adaptative.

Après avoir testé nos prédictions théoriques et méthodologiques à travers une tâche expérimentale contrôlée en laboratoire, nous avons souligné l'importance de mener une expérimentation permettant d'atteindre un optimum entre validité écologique et contrôle expérimental, à travers une tâche de laboratoire appliquée au contexte opérationnel (micromonde). Ainsi, nous nous sommes demandés si les tâches d'ATC permettaient cette adaptabilité. En effet, de nombreux auteurs parlent d'un compromis cognitif entre performance et effort, d'adaptabilité de la charge mentale de travail par le contrôleur aérien (Athènes, Averty, Puechmorel, Delahaye, & Collet, 2002 ; Averty, Collet, Dittmar, Athènes, & Vernet-Maury, 2004 ; Cullen, 1999 ; Hilburn, 2004 ; Histon et al., 2002 ; Majumdar, Ochieng, McAuley, Lenzi, & Lepadatu, 2004 ; Nunes & Mogford, 2003). Cependant, il n'existe aucune démonstration empirique à la fois comportementale et physiologique de cette adaptabilité dans les tâches d'ATC.

Le troisième chapitre empirique et article avait ainsi pour objectif de tester si une tâche complexe d'ATC permettait d'activer un tel compromis se traduisant par une adaptabilité comportementale et physiologique. Nous avons encore observé une baisse des performances, avec une mobilisation croissante de l'effort pour ralentir le déclin de la performance jusqu'au niveau intermédiaire. Au-delà, au niveau très complexe, la performance continuait à baisser (taux d'erreur) ; mais l'opérateur mobilisait moins d'effort pour éviter des perturbations excessives et il mettait en place une stratégie comportementale adaptative. Plus précisément, un compromis performance-effort a été observé, avec un temps de réponse plus court pour garantir un certain niveau de performance (Figure 4.5, p. 105, 106). Nos résultats ont mis en évidence l'activation d'un

compromis cognitif entre performance et effort avec une adaptabilité comportementale et physiologique de l'opérateur, tout comme démontré précédemment avec le modèle de charge mentale de travail d'Hancock et Szalma (2006).

Apports de cette thèse

L'un des apports théoriques est l'approche multidimensionnelle avec l'identification et la définition des trois dimensions majeures de la charge mentale de travail. Ces trois dimensions sont les exigences de la tâche, la performance et l'effort mental. Les exigences de la tâche représentent la charge mentale imposée à l'opérateur. La performance manifeste l'atteinte du (ou des) objectifs de la tâche. L'effort mental est l'énergie que l'opérateur mobilise réellement, face à la tâche imposée.

Le deuxième apport théorique est la validation expérimentale globale du modèle de la charge mentale de travail, de Hancock et Szalma (2006). Ce modèle reprenant les trois dimensions précédentes dans une relation curvilinéaire dynamique, est validé dans sa globalité par nos indicateurs.

Ce travail de thèse a aussi des apports méthodologiques avec une approche multiple de la mesure de la charge mentale de travail. Pour Cegarra et Chevalier (2008), aucune mesure ne peut prétendre évaluer pleinement la charge mentale de travail. Ces auteurs considèrent donc qu'il est nécessaire de combiner différentes mesures pour améliorer la qualité (sensibilité, sélectivité, diagnostic) des indicateurs de charge. En accord avec notre approche multidimensionnelle de la charge mentale de travail, nous avons mesuré chacune des trois dimensions de celle-ci. La mesure des exigences de la tâche, la mesure de performance et la mesure de l'effort mental forment un point de vue global de la charge mentale de travail de l'opérateur et de son adaptabilité.

De plus, nous avons introduit à travers cette thèse, la PEP, une mesure physiologique globale de l'effort mental très présente en psychologie expérimentale, mais absente de la littérature en ergonomie.

Réflexions et perspectives

En psychologie expérimentale, Richter et al. (2016) démontre un effet linéaire des exigences subjectives de la tâche sur la mobilisation de l'effort mental avec la PEP. Cependant, nos expériences montrent un effet curvilinéaire. La mobilisation de l'effort était plus élevée à un niveau intermédiaire de la tâche, alors que les auteurs avaient prédit un niveau de mobilisation de l'effort plus élevé à un niveau très difficile. Cette différence pourrait provenir du *type de tâche utilisé*. Dans de nombreuses études en psychologie expérimentale, l'effet linéaire entre la difficulté perçue et l'effort (théorie de l'intensité de la motivation, Brehm & Self, 1989) a été testée et démontrée. Les tâches utilisées étaient principalement des tâches sollicitant la mémoire et aucun changement de stratégie n'était observé (Richter, Friedrich, & Gendolla, 2008 ; Richter & Gendolla, 2009 ; Wright, 1996).

Une autre explication de cette différence d'effet pourrait émaner du *nombre de niveau de difficulté manipulé*. Richter et al. (2008) manipulait la difficulté en 4 niveaux (facile, modéré, très difficile, impossible). Ils trouvaient une augmentation de l'effort mental à travers le niveau, facile, modéré et très difficile, puis un désengagement au niveau impossible de la difficulté perçue. Dans nos expériences (par exemple, Mallat et al., 2019) nous manipulions 5 niveaux de difficulté (très facile, facile, intermédiaire, très difficile, impossible). Nous avons trouvé une augmentation de l'effort mental à travers le niveau, très facile, facile, intermédiaire, puis la mise en place de stratégie au niveau très difficile avant un désengagement total au niveau impossible. Nous pouvons imaginer que plus nous rajoutons de niveau de difficulté plus nous avons de précision sur la courbe.

De plus, la PEP maximale semble varier selon *la nature de la tâche*. Il n'existe aucune échelle permettant d'établir les valeurs minimales et maximales de la PEP pour un effort mental. Par le biais d'une tâche de mémorisation de lettre Richter et al. (2008), avaient un score de réactivité PEP maximal de -6.14 (ms) et un score minimal allant entre -0.27 et -1.97 (ms). Dans le premier article, à travers la tâche de pointage, nous avons un score de réactivité PEP maximal de -8.22 (ms) et un

score minimal de -1.56 (ms). Alors que dans le troisième article, ayant comme tâche une simulation de contrôle du trafic aérien, nous avons un score de réactivité PEP maximal de -4.25 (ms) et un score minimal allant de -0.89 et -2.12 (ms). Selon Westbrook et Braver (2016), la mobilisation de l'effort peut être modulée par la sollicitation en mémoire de travail. Plus la tâche nécessite de la mémoire de travail, plus la mobilisation de l'effort sera importante.

Outre cela, *l'aspect temporel de la tâche* pourrait aussi expliquer cette différence de PEP. Nous avons vu dans le deuxième article que la pression temporelle favorisait l'adaptabilité comportementale et physiologique avec la mise en place de stratégie. La mobilisation de l'effort était plus importante, avec la pression temporelle. Dans la tâche de pointage avec pression temporelle, la cible s'éloignait, jusqu'à disparaître à travers 75 essais d'environ 6 secondes chacun. Dans la tâche de contrôle du trafic aérien, l'avion (ou les avions) ainsi que les variables à contrôler (altitude, cap), évoluaient avec le temps pendant 8 minutes. Dans cette troisième étude, la mobilisation de l'effort semble proche de la mobilisation de l'effort dans la tâche de pointage sans pression temporelle, qui avait pour score de réactivité PEP maximal -4.25 (ms).

D'autre part, l'évaluation et la mise en évidence des effets de la charge mentale de travail sur l'adaptabilité pourrait être optimisées par des analyses supplémentaires.

Nous pouvons nous demander si les variables d'effort globales de PEP vont dans le même sens que les variables à plus court terme. Cela revient à poser la question de si l'effet curvilinéaire de la charge mentale de travail prédit par le modèle d'Hancock et Szalma (2006) est un modèle très général ou aussi un modèle pour des *processus plus spécifiques*. Pour tester ce questionnement nous pourrions coupler la PEP avec les ERPs. Nous pourrions utiliser la P300 pour sa référence aux ressources attentionnelles disponibles (Hansenne, 2000). Plus la charge mentale de travail sera importante plus l'amplitude de la P300 sera basse. Nous pourrions aussi utiliser la N200 pour l'aspect activation moteur (Kourtis, Sebanz, & Knoblich, 2012). Plus la charge mentale de travail sera importante plus l'amplitude de la N200 sera basse. Dans le cadre de la tâche de pointage, la

CNV (Component Negative Variation) pour l'effort préparatoire pourrait être observé. La CNV serait mesuré environ 200 ms avant l'apparition du mouvement. L'amplitude de la CNV pourrait être affecté par la charge mentale de travail.

A côté de cela, la mesure des *ondes* Alpha, Beta, Delta, Gamma, Thêta pourrait être une mesure de l'activité cérébrale à explorer. L'activité des ondes Alpha et Thêta sont très utilisées dans les études sur la charge mentale de travail (Dasari, Shon, & Ding, 2017 ; Puma, Matton, Paubel, Raufaste, & El-Yagoubi, 2018). La baisse de l'activité Alpha serait liée à des niveaux de vigilance augmentés, alors que la diminution de l'activité Thêta serait liée au traitement de l'entrée visuelle (Barry, Clarke, Johnstone, Magee, & Rushby, 2007 ; Bazanova & Vernon, 2014). Dans la littérature, une augmentation de l'activité Thêta dans la zone frontale associée à une diminution de l'activité Alpha dans les zones pariétales, serait corrélée à une augmentation de la charge mentale de travail (Berka et al., 2007 ; Borghini, Astolfi, Vecchiato, Mattia, & Babiloni, 2014 ; Holm, Lukander, Korpela, Sallinen, & Müller, 2009). Nous pourrions donc analyser les bandes de fréquence pour les ondes Alpha et Thêta, selon nos cinq niveaux de difficulté.

D'autres perspectives pourraient venir s'ajouter à ce travail de thèse. Nous pensons notamment à l'aspect décroissant de la charge mentale de travail faisant suite à un pic de charge mentale de travail maximale qui n'a pas été pris en compte dans cette thèse. Cumming et Croft (1973), mettent en évidence un modèle entre la charge mentale de travail croissante et décroissante en évolution constante et la performance. Les auteurs montrent un *phénomène d'hystérésis* (Figure 9). L'hystérésis fait référence à la forme de la courbe dont l'évolution ne suit pas le même chemin selon qu'une cause extérieure augmente ou diminue. Après une charge mentale de travail élevée, le participant a une performance détériorée avec une charge mentale décroissante. En ATC une forte proportion d'accidents a eu lieu après une période de charge mentale de travail élevée suggérant que l'effet d'hystérésis ayant peut-être fortement contribué (East, 1993 ; Farrell, 1999 ; Smolensky, 1990). Il serait intéressant de tester ce phénomène afin de comparer nos résultats qui disposaient

d'une charge mentale de travail croissante (ayant comme pic de charge le niveau intermédiaire), à une charge mentale de travail décroissante. Pour cela, il faudrait que chaque participant passe successivement les différents niveaux de charge mentale de travail pouvant être, facile, intermédiaire, facile.

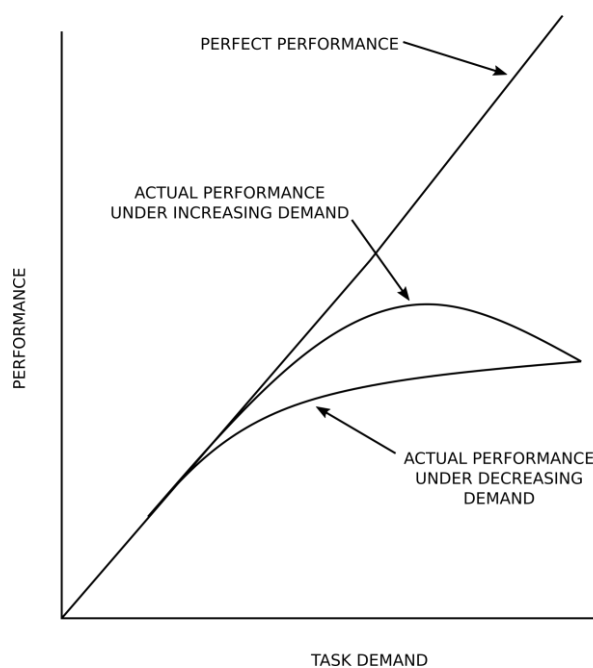


Figure 9. Le phénomène d'hystérésis dans le traitement de l'information humaine par Cumming et Croft (1973).

De plus, la notion d'*expertise*, n'a pas été abordée dans cette thèse. Pour les trois expériences, nous avons changé les exigences de la tâche ainsi que les tâches, mais pas la population. La littérature sur la prise de décision par des experts suggère que les experts prennent de meilleures décisions en partie grâce à des stratégies efficaces d'attribution de l'attention (Ericsson, 2006 ; Ericsson et Lehmann, 1996). À mesure que l'expérience spécifique à une tâche se développe, les pilotes développent des représentations structurées de l'environnement de la tâche dans la mémoire à long terme qui les aident à constituer un modèle mental de leur environnement de tâche actuel (Doane, Sohn, & Jodlowski, 2004). L'expérience permet aux pilotes experts de s'occuper plus facilement des informations pertinentes lors de la prise de décision (Khoo & Mosier, 2005 ; O'Hare,

2003). Bunce et al. (2011), ont examiné la relation entre la réponse hémodynamique dans le cortex préfrontal dorsolatéral, la charge mentale de travail et le niveau d'expertise dans l'exécution de tâches. Les résultats ont montré qu'une plus grande expertise était associée à une oxygénation relativement faible (activité neurale moindre) à des niveaux de charge mentale de travail faibles à modérés, mais à une oxygénation plus élevée et à de meilleures performances à des niveaux de charge mentale de travail élevés. Pour les novices, l'oxygénation était plus élevée à des niveaux de charge mentale de travail modérés, mais chutait précipitamment à des niveaux de charge mentale de travail plus élevés, ainsi que des performances compatibles avec un désengagement de la tâche. Il serait alors intéressant de tester les experts du contrôle, pour voir s'ils s'adaptent selon les mêmes critères face à la charge mentale de travail imposée. Pour ce faire, il faudrait soumettre à la troisième expérience des contrôleurs aériens, ou des candidats finissant leur formation de contrôle du trafic aérien cela n'ayant pas pu être réalisé dans le cadre de cette thèse.

Une autre perspective pour prolonger ce travail, serait une expérience sur simulateur auprès de contrôleurs aériens. Cette simulation permettrait de tester les effets de la charge mentale de travail sur l'adaptabilité comportementale et physiologique, ainsi que notre approche multiple de la mesure dans un *environnement écologique* situé au plus proche de la situation de travail. Les objectifs principaux du contrôle sont de superviser le trafic aérien s'écoulant sur un secteur de contrôle et d'en assurer la sécurité, notamment en détectant et résolvant les situations conflictuelles susceptibles de s'y produire. Aux vues de nos résultats dans l'expérience sur micromonde ATC, il serait intéressant de tester à travers 5 niveaux de complexité sur simulateur, le moment le plus opportun pour l'introduction d'un outil d'aide, par exemple un outil d'aide à la gestion des situations conflictuelles. Est-ce que l'introduction d'un outil d'aide au niveau intermédiaire de la complexité (qui représente une charge mentale élevée avec la plus forte mobilisation d'effort dans

l'expérience sur micromonde ATC) permettrait une baisse de la charge mentale de travail avec une meilleure performance ?

Les résultats de cette thèse ont des applications pratiques sur la modélisation de la charge mentale de travail, la formation et la conception d'outils, axées sur l'interaction homme-machine.

Nous avons généré des études avec un fort contrôle expérimental pour tester un modèle de la littérature ergonomique. Puis nous avons voulu généraliser ses résultats à une classe de situations plus large, c'est-à-dire de proposer une certaine *validité écologique* (Hoc, 2001). Nos études font référence au terrain et visent à produire un corps de connaissances permettant l'amélioration des conditions de travail (Leplat, 1997).

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